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Survey of Antenna Design Computer Models

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Space Systems Development Department

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13. ABSTRACT (*Maximum 200 words*)

This report presents an overview of existing computer models available for antenna design and performance evaluation. It discusses the various solution techniques, such as the method of moments, finite element and high frequency (asymptotic) techniques, and their limitations with respect to frequencies, computer resources available, and antenna type and surrounding structures needed to be modeled. Sample problems are presented along with availability of the codes. Current areas of research are also discussed.

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Antenna Design Model Survey

I. INTRODUCTION

Early antenna problems were solved by analytical integration of the fields. With this technique, considerable effort goes into manipulating solutions into a form where the computational effort is minimized.[1] Analytic techniques are not easily adaptable to computerized solutions and so become relatively obsolete as the complexity of the antenna to be modeled and its surroundings increases. They can be useful as a first cut solution, though, and as an aid to understanding.

The publication of Harrington's classic paper "Matrix Methods for Field Problems[1] in 1967, marked the beginning of computerized solutions of electromagnetic problems. Since then, this area has been the subject of much research effort and has seen rapid progress. The finite element method was first applied in electromagnetics by Peter Silvester of McGill University in 1969, who used it to solve a waveguide problem.[2] Keller[3,4] did pioneering work in high frequency (asymptotic) techniques in the early 1960's.

The increases in the computer industry in both speed and storage capabilities has fostered the growth in antenna modeling to the point where personal desktop computers have enough capability to do very sophisticated and computationally intensive antenna design problems. To a large extent, the advancement in numerical antenna modeling is directly dependent on and parallels the continued advancement and availability of super computers with increased speed and memory. It also has profited by the development of interactive computer graphics for visualizing device geometry and field distributions, and the advancement of numerical analysis techniques.

Figure 1 shows the relationships between several E&M (electromagnetic) analysis techniques.[5] Computerized solutions can be broken into the two main areas of numerical techniques and high frequency/asymptotic techniques. The code best suited for a particular antenna problem depends on the type of antenna, the shape, size, and material properties of the antenna and surrounding structures, the operating frequency, and the available computer resources.

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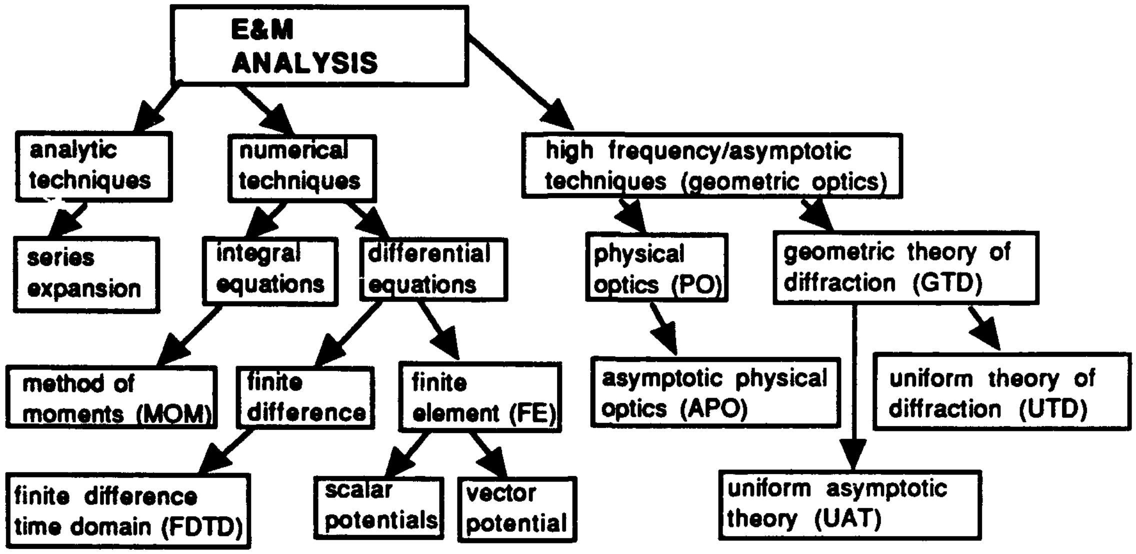


Figure 1. Family of E&M analysis techniques.

As shown in Figure 1, numerical methods are based on solving Maxwell's equations with either integral equations (IE) or differential equations (DE). With the differential equation method, Maxwell's equations are written in the familiar curl and divergence relations. With the integral equation method, the equations are written in a source-integral form.[6] Though physically equivalent, IE and DE methods have relative strengths and weaknesses due to numerical limitations. DE methods can handle complicated geometry and material properties while IE methods, like the method of moments (MOM), excel in open boundary problems. Far fewer unknowns are required in IE methods, but the matrices are full, leading to considerable numerical difficulties. In contrast, for the DE methods, the matrices are sparse, banded and symmetric, and allow very efficient matrix methods to be used.[5]

In general, MOM[7] is the technique of choice for antenna problems involving small (less than 10 λ (wavelengths)) bodies with perfectly conducting surfaces or thin dielectrics. This method gives an exact solution for the near and far-fields, the input impedance, and the efficiency. The structure is broken up into sections of wires or plates of dimension $\lambda/4$ to $\lambda/10$. Unfortunately, for structures much greater than 10 λ this technique quickly approaches the limits of most computers both in memory and computational time required.

Above 10 λ, high frequency (asymptotic) techniques, such as the geometric theory of diffraction (GTD), give a good approximation to the actual solution. The GTD technique uses ray tracing and diffraction to predict the relative far-field patterns. It is easy to use and can model very

large structures quickly. It cannot determine input impedance and absolute field intensities, however, and can give erroneous solutions for certain structures where there are resonances. It also is not good for modeling structures with fine structural details less than a wavelength in size. Reflector codes generally use some type of high frequency technique.

The finite element (FE) and finite difference time domain (FDTD) codes are best for small heterogeneous bodies. These codes are very memory and computationally intensive and ideally require a mesh generator code to set up the structures. These codes have good potential for the future when greater computing power is available because of their flexibility to handle any type of structure or material.

Various hybrid techniques are also used to combine the MOM, FE or FDTD codes with a GTD code to model large structures accurately.

The first section of this report will discuss the various analysis methods in more detail. The next section will summarize specific codes that are available now. After that, a few sample problems will be discussed. Finally, recommendations on use of the antenna codes will be made and the general findings of this study summarized.

II. SOLUTION METHODS

A. Method of Moments (MOM)

The method of moments uses equations written in an integral form. A Green's function, which is defined to be the electric field intensity at one point in space due to an electric current element at another point subject to specified boundary conditions,[8] is used to calculate the effect of the current elements on other elements and free space.

For the MOM method, the structure being analyzed is divided into a number of straight wire subsections or surface patches which are each small compared to the wavelength. Each of these elements is then considered to be a point source radiating to, and interacting with, all of the other elements making up the system geometry. These various interactions are represented by a set of simultaneous equations, which is represented in a matrix notation.[9] Equation (1) is the resulting matrix equation

$$[Z]\,[I] = [E] \tag{1}$$

where Z_{ij} is the interaction matrix, I_i is the current on subsection i, and E_j is the electric field on subsection j.[10] The term Z_{ij} represents the field on subsection i due to a unit current on subsection j. E_j is the excitation matrix which is specified by the problem. I_i is the current matrix which are the unknowns. Equation (1) can be solved for the currents by matrix inversion. Lower/upper decomposition is the technique usually employed.[10] The number of operations needed to solve the matrix is $N^3/3$ when using the full interaction matrix in a forward elimination/backward substitution technique.

Once the currents and current densities are known, it is then a simple matter of matrix multiplication with a suitable Green's function to obtain the field at any point in the near or far field of the structure. Coupling between the terminal of antennas and the input impedance of any antenna is easily calculated, and proper positioning and incrementing of the source with respect to the structure will allow the monostatic and/or bistatic cross section of the object to be calculated.[9]

In general, the method of moments (MOM) is the technique of choice for problems involving small (less than 10 λ (wavelengths)) bodies with perfectly conducting surfaces or thin dielectrics. The structure should be broken up into either wires or surface patches of dimension $\lambda/4$ to $\lambda/10$.

The amount of segmentation needed is dependent on where the patch or wire is located, with regions close to the antenna and near the edges of structures usually needing higher segmentation than other regions. Surface patch modeling represents a perfectly conducting surface by a vector electric current density on the surface. A surface can be represented by either a wire grid or surface patches, however, surface patch models give a more accurate representation of the currents on a surface, and require fewer unknowns per square wavelength of surface area than a grid model.[11]

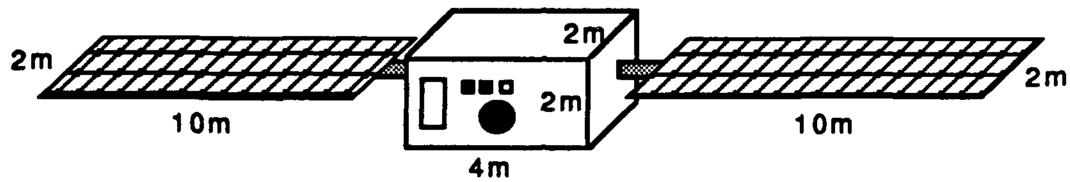
There is considerable research going on developing new basis functions for the MOM codes. A basis function describes the distribution of the current on the wire or patch segments. The type of basis function used will affect the amount of segmentation needed to achieve a given degree of accuracy. The simplest type of basis function is the piece wise linear function. With this function, each segment will have a different fixed current. Unfortunately, the staircasing effect can cause some non-linearity with this function. Segmentation of at least $\lambda/10$ is usually needed. Piece wise sinusoidal basis functions are better, and, with these, $\lambda/5$ segmenting can be used. There are also triangular basis functions. Basis functions for surface patches are more complicated.

Various types of weighting functions can also be used. The moment method uses a numerical technique called the Method of Weighted Residuals, where the weighting functions are used to zero out the residual at various points in the solution.

The MOM method gives an exact solution for the near and far-fields, input impedance, and efficiency. It accurately takes into account mutual coupling effects. For a perfectly conducting surface or thin dielectric, the MOM method can be 10 times faster than a finite element or finite difference time domain code. This is mainly because the outer boundary conditions are inherently built into the formulation. Solving Maxwell's equations outside the scattering body, which for the partial differential equation solvers often consumes the dominant portion of CPU time and memory, is not required.

For structures much greater than 10 λ the MOM technique quickly approaches the limits of most computers both in memory and computational time required. As an example of this, consider modeling a satellite structure such as the one shown in Figure 2. To find the number of unknowns (N), the total surface area (in λ^2) is first calculated. For each λ^2, there are 16 segments if the area is subdivided into $\lambda/4$ sections. This

is multiplied by two to account for current traveling in both directions for a total of 32 unknowns for each λ^2. If the surface area is 80 λ^2 (80 m^2 for 300 MHz) as for the structure shown in Figure 2, then the total number of unknowns is 80 x 32 = 2560. The impedance matrix that must be solved is this number squared or 6,553,600. Each number is complex so there are 2 words per matrix element. Using 4 bytes per word we arrive at 52 MBytes of RAM memory needed to solve this relatively small problem.



Total Surface Area: $80m^2$

Figure 2. Example satellite for modeling with MOM code.

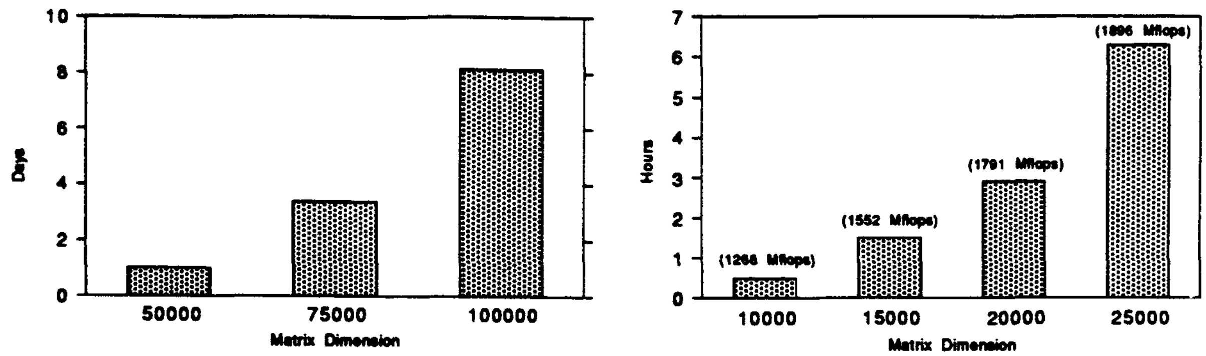
Using a CRAY, a factor of speed increase on the order of 200 is obtained over a VAX equivalent machine. An out-of-core solution solver allows a larger number of unknowns to be solved. As a rough estimate, 20,000 unknowns on a CRAY would take 1 day of CPU time.

Work is being done at the Jet Propulsion Laboratory (JPL)[12] and Sandia National Laboratories[13] on solving MOM problems on parallel processing machines. For parallel processing machines, the optimized library routines, usually involving block decomposition, for solving the matrix equation must be implemented. Both in-core and out-of-core solutions can be used. JPL solved a problem with 30,000 unknowns on an Intel i860 512-node DELTA mesh. It was executed in 6.2 hours with the matrix factorization taking 2.84 hours. This represented a machine performance of 6.2 Gflops. For the 30,000 unknowns problem, over 14 gigabytes of storage is needed. With a total of 90 gigabytes disc storage on the DELTA machine, JPL has plans to run a problem with over 70,000 unknowns. They also have plans to model reflectors with their MOM code.

Intel has developed the ProSolver-DES software which is a high performance dense linear equation solver. It is optimized for Method of Moments calculations and runs on the Intel iPSC/860 parallel super computer. This computer is configurable for up to 128 nodes (independent processors). With 128 nodes, it runs 66 times faster than the largest Cray supercomputer, the YMP8, which costs \$25-\$30 million.

The DES software cost is \$7K to \$45K depending on the number of nodes. For a 32-node machine the cost is \$25K. An iPSC/860 machine with 90 GBytes of storage and 128 nodes would cost ~\$4 to 5 million. It has an out-of-core solver. The Computational Physics Division at NRL has a 32-node iPSC/860.

Figure 3 shows two charts of matrix factor time versus matrix dimension for a 64-node and a 128-node iPSC/860 machine.



(a) 128 node machine (b) 64 node machine

Figure 3. Matrix factor time versus matrix dimension for an iPSC/860 parallel super computer[75]

One technique used to reduce the time for the matrix inversion is called Banded Matrix Iteration (BMI).[10] This technique, used in the GEMACS hybrid code, uses the fact that the values of the elements of the interaction matrix decrease with increasing distance from the main diagonal. A region is chosen such that most of the large elements fall within a band centered on the main diagonal. The number of minor diagonals falling within this region on either side of the main diagonal is the bandwidth M of the banded matrix. The larger the bandwidth, the more quickly the solution converges, however, the more operations are needed to perform the matrix inversion. The out-of-band elements are considered second-order effects in an iteration equation.[10] There is a tradeoff between bandwidth and convergence, however, this technique can reduce the computational time of the matrix inversion by as much as 3.5 times.

Canning and others[14,15] are working on an IML (impedance matrix localization) technique where the matrix size is on the order of 100 N

rather than N^2. With this method, directional basis and testing functions are used to localize all of the significant interactions within the impedance matrix to a small (~N) number of clumps of large numbers, while all the other numbers can be approximated by zero. They have had some success for 2D and dielectric body of revolution (DBR) problems. The method is much harder to implement for 3D problems.

Other researchers[16] are also examining various techniques for reducing the computational time of the MOM method.

Some MOM codes can model thin dielectrics. For this case, a finer mesh is needed. Roughly $\lambda/(\sqrt{\varepsilon_r} \times n)$ should be used, where ε_r is the relative dielectric constant and n is the number of segments per wavelength the section would be broken up into for a perfectly conducting case.

Either the electric field integral equation (EFIE) or the magnetic field integral equation (MFIE) can be used in the MOM solution. The EFIE is a better technique for handling flat plates and wire structures, but is considerably more difficult to implement for arbitrarily shaped objects than the MFIE.[17] The MFIE can handle closed bodies only. The CFIE (combined field integral equation) is a combination of the two techniques.

Modeling patches is difficult because the current on the patch must be defined in two dimensions. Also, in general, the current on the front and back surfaces of a patch are not equal. If the structure is enclosed the currents on the inside of the surface do not affect the outer environment. With the EFIE technique, the surface can be approximated by a zero thickness plate with the vector sum of the top and bottom currents at the center of the plate.

Triangular patches are preferable for modeling arbitrarily shaped surfaces. They can accurately conform to any geometric surface or boundary, the patch scheme is easily specified for computer input, and the patch density can be easily varied. Rectangular patches limit structures to curvature in one dimension only.[17] Curvilinear triangular patch codes are currently being developed which allow for more accurate modeling of curved surfaces with less segmentation required.[18,19]

The main limitation of the MOM method is that the required computer storage ($\propto N^2$) and CPU time ($\propto N^3$) increases as the electrical size of the antenna or scatterer increases. The solve time for the matrix overtakes the matrix generation time when there are more than ~2000 unknowns. Another major limitation is that the MOM method cannot easily handle dielectric materials other than thin patches.

The MOM method can be implemented in a number of ways. Errors can occur when the structure is not broken up into a fine enough grid, particularly in certain critical regions such as near the radiating element and around edges, and if the feed is not accurately modeled. Researchers at K. U. Leuven in Belgium found a simple implementation of the code for a microstrip backfire antenna gave fairly large errors until they modified the code to include a coaxial feed model with a probe-current source. Sophisticated attachment modes were determined to ensure a continuous current flow from the probe to the connecting patches.[20]

Commonly used and available MOM codes are listed in Table I. For most of the codes the maximum number of unknowns (wire or patch segments) that can be modeled is dependent on the amount of memory that the computer they are installed on has and the amount of time the modeler is willing to wait for a solution. For these codes, the source code is provided and the arrays can be easily redimensioned.

Table I. Common MOM Codes

Name of code	Source	Approx. Cost	Public Domain Software?	Maximum Number of Unknowns
NEC	Lawrence Livermore National Laboratory	$850	yes	dependent on computer resources
GEMACS	Rome AFB	$250	yes	dependent on computer resources
MiniNEC	Electromagnetics Society		yes	300
ESP4	Ohio State University	$250	yes	dependent on computer resources
SPW3D	Univ. of Illinois	$30,000	no	2000- workstation 20,000- CRAY computer
AWAS	Artech House Publishers	$290	no	150
Extended AWAS	Prof. Harrington Syracuse Univ.	$3,000	no	500
DBK code	Univ. of Miss.	distribution cost	yes	dependent on computer resources
Patch code	Sandia National Laboratory	distribution cost	yes	dependent on computer resources

More information regarding each of these codes is presented in Section III. Some of the other companies, universities, and government labs that have developed MOM codes that are either proprietary or developmental are listed in Table II. Many of these institutions' codes are simply a standard code with some modifications added.

Table II. Institutions having MOM Codes

Institution	Location
McDonnell Douglas	St. Louis, MO
Martin Marietta	Denver, CO
Auburn University	Auburn, Alabama
Syracuse University	Syracuse, NY
University of Belgrade	Belgrade, Yugoslavia
University of Manitoba	Canada

B. Finite Element (FE)

In FE modeling, the antenna structure and surrounding area is broken up into finite element sub regions. The electromagnetic properties of each element are specified along with the governing equations relating the properties of the element with its nearest neighbors, and the resulting matrix equations, based on Maxwell's differential equations, are solved using conventional methods.[5] This technique is capable of modeling all aspects of field behavior. The FE code solves problems in the frequency domain, but can also be used for transient analysis. The FE code generates a sparse matrix of dimension N x N (where N is the number of elements) which must be inverted.

Figure 4 shows a sample grid structure of a waveguide slot antenna.

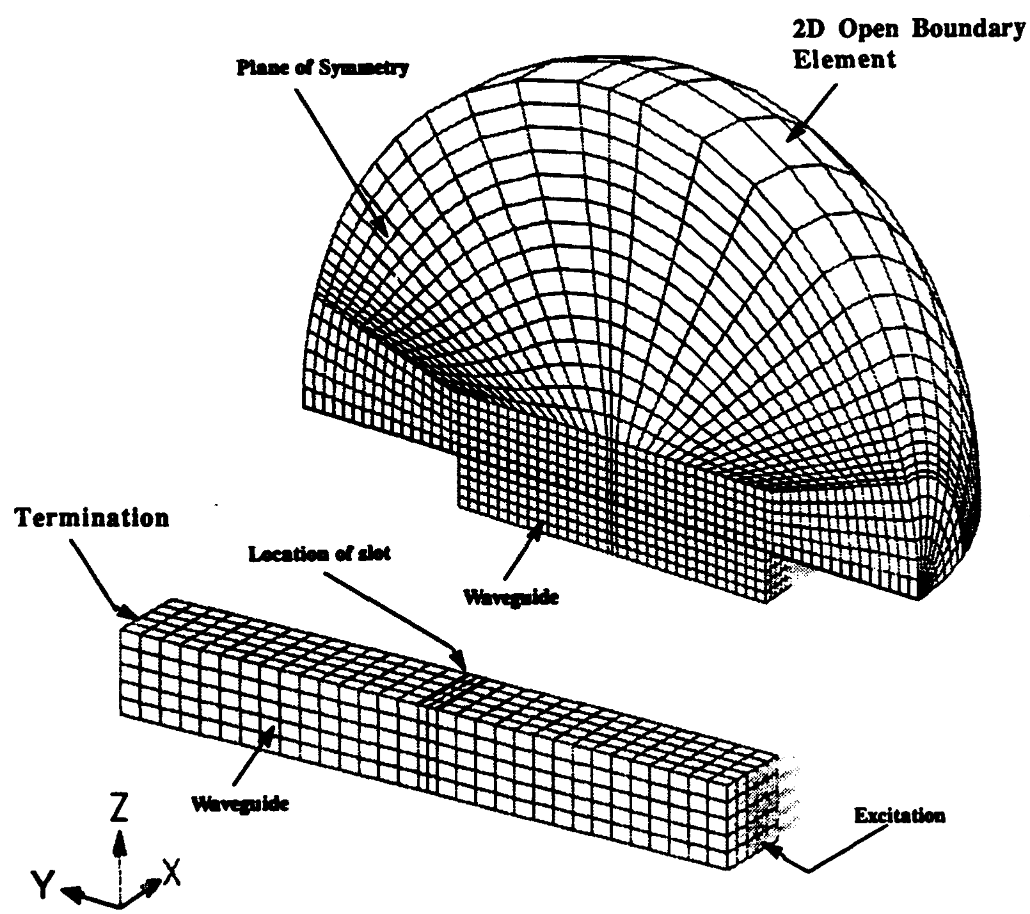


Figure 4. Grid structure for finite element modeling of a waveguide slot antenna and surrounding air.[21]

Finite elements are frequently shaped like triangles or rectangles in 2D work and tetrahedrons or boxes in 3D work. Irregular meshes, and elements with curved sides can also be used. The accuracy of the method depends upon the number of elements used to make up the grid and the type of approximation functions used in each element. The approximation functions represent the distribution of fields throughout the finite element cell. These will usually be expressed in two dimensions for a 2D cell, and in three dimensions for a 3D cell. The approximation functions are typically first- to fourth-order polynomials. Higher-order polynomials provide much more accuracy than lower-order polynomials but are less flexible for modeling irregular boundaries.[2]

FE codes are currently used extensively for waveguide and closed cavity problems. Their extension to antenna problems has been hampered by the difficulty of creating open boundary conditions, the need to transform the near field solution to the far field, and the large number of elements required to model simple structures, which dictates the use of a mesh generator.

The first difficulty with adapting FE codes to antenna problems is creating an absorbing (or transmissive or open) boundary condition so that the near- and far- fields are accurately modeled. Many codes have reflective boundary conditions and are suitable for EM problems such as coax lines and waveguides. With an open boundary condition, the fields do not reflect and so simulate an air to air boundary. This type of boundary condition is difficult to implement. With an open boundary condition, the FE mesh extends beyond the antenna structure and into the air and the near fields of the antenna are calculated. Another code is then written which uses Fourier Transforms to translate the near field pattern to a far-field pattern. Alternately, the mesh can be extended into the far field of the antenna. This can require a prohibitively large number of elements, though. One method to reduce the number of cells is to gradually increase their size as they move away from the antenna.

With the FE method, a finer mesh, $\lambda/15$-20, than that needed for the Method of Moments is needed for accurate solutions. The large number of elements needed for even small problems necessitates the use of graphics pre- and post-processing and a mesh generator such as Patran or MSC/XL.

The FDTD and FE codes are generally better when using dielectric materials, otherwise the MOM method is preferable for antenna problems. Table III lists some commonly available FE codes which can be applied to

antenna problems. More information regarding each of these FE codes is presented in Section III.

Table III. Common FE Codes

Name of code	Source	Approx. Cost	Public Domain Software?	Maximum Number of Unknowns
EMAS	MacNeal-Schwendler	$2000/month	no	20,000 (practical limit)
FE Code	Univ. of Illinois	$30,000	no	20,000 (practical limit)
FERM	MIT Lincoln Laboratory			

For these codes the maximum number of unknowns that can be modeled is given a practical limit which is dependent on the amount of memory that the computer they are now installed on has (if the machine does not have virtual memory or an out-of-core solution solver) and the amount of time the modeler is willing to wait for a solution. There are several other available FE codes which are not listed that are suitable for general electromagnetic analysis but not antenna analysis. References 2 and 71 give a more comprehensive listing of these.

C. Finite Difference Time Domain (FDTD)

The FDTD method, introduced by Yee[22], is similar to the FE method but solves the problem in the time domain instead of the frequency domain. The structure and surrounding area is split into a grid of nodes. The grid can be either two- or three-dimensional depending on symmetry. Three-dimensional problems are much more computationally intensive and so any symmetry in the structure should be utilized to simplify the problem. The material properties at the nodes are specified along with the excitations. The code approximates the given differential equation by the finite difference equivalent that relates the dependent variable at a point in the solution region to its values at the neighboring points. At each time step, the steady state electric and magnetic fields are computed for each successive node and its nearest neighbors. This process is repeated over and over again until the fields reach steady state. This code is well suited for a parallel processing computer such as the Connection machine.

Because there is no matrix inversion, the solve time and memory requirements are proportional to N, where N is the number of nodes

(unknowns). The method of moments, by comparison, which involves a matrix inversion step, requires N^2 in storage and N^3 in running time.[23] This advantage is deceptive because a finer mesh, $\lambda/60$, is sometimes needed to get reasonable modeling results in the FDTD method.[70] Also, sometimes several thousand time steps must be made to reach a stable solution and this is computationally intensive.

The frequency domain solution to the problem can be obtained by stimulating the grid with an impulse function and doing Fourier transforms on the time solution at each grid point.

The conventional finite difference method uses the differential form of Maxwell's equations like the finite element method but the problem is solved by placing a regularly spaced grid of points over the domain of interest and solving the differential equations at each point. This technique is less flexible than the finite element method, which permits meshes of irregularly shaped elements.[2] Irregular meshes are desirable because they can accurately model curved or diagonal boundaries and the accuracy of the mesh can be varied.

The FDTD method is very straightforward and robust, however, there are several problems that have slowed its acceptance and general use. Initial problems that were overcome in the early 1980's included the implementation of an open boundary condition, the simulation of an arbitrary incident wave, and the calculation of the far fields given near-field data.[23] The open boundary condition allows the FDTD method to be applied to antenna problems.[24]

Current problems relate to computer resources, such as having a computer fast enough and with enough memory to handle large problems. Optimally, the computer must also have graphics capabilities to visualize the problem and automatically generate the mesh.

Another problem with FDTD codes is that they generally use a Cartesian coordinate system and can't handle arbitrary shapes like curved surfaces without a staircasing effect. Staircasing greatly decreases the accuracy of solutions for curved surfaces. Current efforts are being made to utilize conformal (non-uniform) grids, so that curved surfaces can be modeled more easily.[25] The problem is difficult, though, because algorithms must be developed for determining who the nearest neighbor cells for each individual cell are. With a conformal grid, greater accuracy can be achieved with larger segmentation, resulting in considerable savings in computer processing time and memory.

Other current research efforts involve improvements to the absorbing boundary condition[26-29], and the use of variable step sizes[30]. The complexity of the absorbing boundary conditions is dependent on how

close the boundary is to the antenna surface. Absorbing boundary conditions in the far-field need only to take into account first order effects, and so are relatively simple to implement. The disadvantage of using them is that many more cells are needed to grid the system out to the far-field.

The FDTD and FE codes are better when using dielectric materials, otherwise the MOM method is up to 10 times faster. The FDTD code does not handle dispersive media. One disadvantage of the time domain method is that the larger the body, the finer the grid needed to converge the solution and get stable results.[31]

FDTD modeling is currently an area of intense research and modeling activity. This is because of its flexibility for handling large complicated problems and its suitability for parallel processing machines. Available FDTD codes are listed in Table IV. For these codes the maximum number of unknowns that can be modeled is given a practical limit which is dependent on the amount of memory that the computer they are now installed on has (if the machine does not have virtual memory or an out-of-core solution solver) and the amount of time the modeler is willing to wait for a solution.

Table IV. Available FDTD Codes

Name of code	Source	Approx. Cost	Public Domain Software?	Maximum Number of Unknowns
FDTD Code	Univ. of Illinois	$30,000	no	20000 (practical limit)
TSAR	LLNL	$550-$750	yes	1,000,000 (practical limit)
FVTD	Shank			
EMDS	Cray Research, Inc.	$80-$160K/year	no	1 billion (on Cray machine)

More information regarding each of these codes is presented in Section III. Many other companies, universities, and government labs also have developed FDTD codes that are either proprietary or developmental. Table V gives a listing of some of these.

Table V. Institutions with FDTD Codes

Institution	Location
McDonnell Douglas Research Labs	St. Louis, MO
Northwestern University	Illinois
Georgia Institute of Technology	Atlanta, GE
Pennsylvania State University	State College, Pennsylvania
The University of Manitoba	Manitoba, Canada
Sandia National Labs	
University of California-Davis	Davis, CA
Oak Ridge National Laboratory	Tennessee
University of Utah	Utah
New Mexico State University	New Mexico
University of Regina	Canada
Syracuse University	Syracuse, NY
Lockheed Palo Alto Research Laboratories	California
Phillips Laboratory	
Auburn University	Auburn, Alabama
University of Kansas	Kansas
State University of New York	Binghamton, New York
Arizona State University	Arizona

D. Geometric Theory of Diffraction (GTD) and Other High Frequency Methods

High frequency techniques for solution to EM problems can be used reliably when the wavelength of the radiation is small in comparison to the size of the scattering objects. Large structures can be modeled quickly and easily.

Most high frequency techniques begin with geometric optics (GO), where the fields scattered by the object are determined by the optics principles of ray tracing and reflection coefficients. Basically, the EM field is reduced to a series of incident and reflected rays which are traced through the system. GO was originally developed to analyze the propagation of light where the frequency is sufficiently high that the wave nature of light need not be considered.[32]

The geometric theory of diffraction (GTD) is based on the superposition of geometric optics and diffracted ray fields. The principles of diffracted ray paths, including creeping waves and diffraction coefficients are used. GTD uses a ray tracing technique, following the ray from the source through a series of reflections and/or diffractions from plates, cylinders, and other structures. Each scattering center is treated as a local source of electromagnetic energy, and the contributions from all sources are summed at the field point.[9] Figure 5 shows an incoming ray scattering off the corner of a wedge. GTD can predict rays beyond the shadow boundary of an object, whereas with simple geometric optics, no rays travel beyond the shadow boundary.

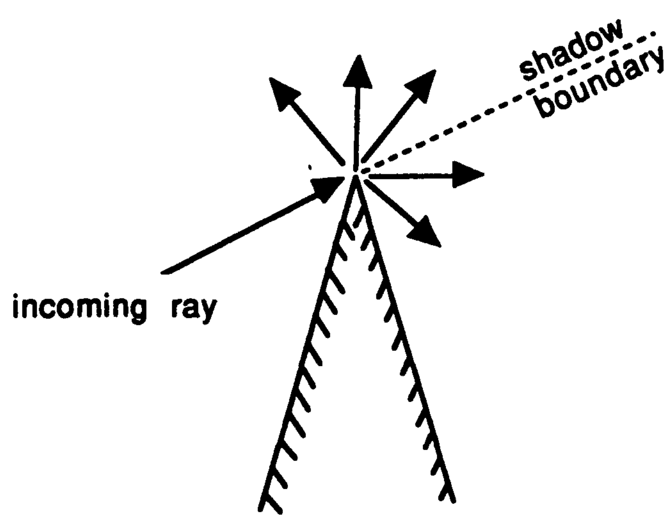


Figure 5. A ray being diffracted from a wedge corner

Away from the point of diffraction, the GTD diffracted ray field behaves just like a geometric optics (GO) ray field. GTD was introduced by Keller[3] is the late 1950's. His postulates were:

1. The diffracted field propagates along ray paths that include points on the boundary surface. These ray paths obey the principle of Fermat, known also as the principle of shortest optical path.
2. Diffraction, like reflection and transmission, is a local phenomena at high frequencies, and depends only on the nature of the boundary surface and the incident field in the immediate neighborhood of the point of diffraction.
3. A diffracted wave propagates along its ray path so that power is conserved in a tube of rays and the phase delay equals the wave number times the distance along the ray path. [32]

The purely ray optical field description of the GTD fails within the transition regions adjacent to the shadow boundaries where the GTD diffracted fields generally become singular. The angular extent of the transition region varies inversely with frequency and also depends on some characteristic distances. This failure of the GTD within the shadow boundary transition region can be patched up with uniform versions of GTD such as the uniform geometrical theory of diffraction (UTD)[33] and the uniform asymptotic theory (UAT).[34,35] Edge and surface diffracted fields with appropriate transition functions provide the uniform corrections and result in a continuous total field if a sufficient set of terms is superimposed. The fields are determined by multiplying the appropriate coefficients, spread factors, and transition functions for the various scattering centers along the ray path.[36,37]

The limitations on the UTD method mainly involve the relative size of the structures to be modeled. Distances and lengths at least on the order of a wavelength are required due to the approximations involved.

Physical optics (PO) is another method of calculating scattered fields which is more general than geometric optics. Geometric optics is frequency independent, while physical optics reduces to geometric optics in the high frequency limit. With PO, the surface currents on the illuminated side of the scattering body are calculated from the cross product of the normal to the surface and the incident field. The currents at the surface in the shadowed regions are zero. The surface currents are integrated to find the scattered fields, taking frequency dependence into account. Both GO and

PO do not calculate fields in the forward scattering direction and cannot correctly predict a non zero field in the shadow region even though one will exist there. Unlike, diffraction theory, they only calculate fields in the back scattered direction.[32] The physical theory of diffraction (PTD)[35,38] is a correction to PO to include diffraction.

Other high frequency methods are asymptotic physical optics (APO), edge diffraction theory (EDT)[39], and the uniform asymptotic theory (UAT)[34]. These high frequency techniques in general work well for modeling electromagnetic wave interactions with electrically large, perfectly conducting structures. However, these approaches are difficult to apply when the structures have reentrant features supporting multiray regions, or material compositions and surface treatments.[23] They are insensitive to details of the scattering surface of the order of λ or less, and the surface wave diffraction and multiple scattering effects are not taken into account.

Table VI lists some available HF codes. These are described in more detail in Section III.

Table VI. Common HF and GTD Codes

Name of code	Source	Approx. Cost	Public Domain Software?	Type of code
NEWAIR	Ohio State University	$250	yes	UTD code
NEC-BSC	Ohio State University	$250	yes	UTD code
Georgia Tech	Georgia Tech Research Institute	distribution costs	available to Navy	PO code

Many other companies, universities, and government labs also have developed HF codes that are either proprietary or developmental. Table VII gives a listing of some of these.

Table VII. Institutions with HF and GTD Codes

Institution	Location
McDonnell Douglas	St. Louis, MO
Martin Marietta	Denver, CO
Department of Electrical Engineering Polytechnic University	Farmingdale, NY
Department of Electrical Engineering University of Florence	Florence, Italy
Naval Pacific Missile Test Center	Point Mugu, CA
General Dynamics	Fort Worth, TX

High frequency techniques remain essential for solving antenna and scattering problems involving large structures such as airplanes, spacecraft, missiles, tanks, and ships. But, at present, their implementation on a computer is rapidly changing. Due to increases in computer capabilities, the need for general CAD programs which can automatically manage the geometrical modeling and ray searching is more and more pronounced. Much of the work in the scientific community is currently being put into interfacing HF codes to CAD programs. Some of this work is discussed further in Section H on RCS (radar cross section) codes.

E. Hybrid Codes

Many antennas lend themselves to an almost exact analysis by the MOM method, however, modeling the platform and surrounding areas is prohibited by the computer resources required. A hybrid code uses the MOM, FE or FDTD techniques to characterize the antenna and a high frequency technique like GTD to model the surrounding area.[40]

In one hybrid method, the antenna problem is first solved for the currents on the wire or patch segments. The GTD code then uses these values as input, and does the analysis through the rest of the system.

In a second hybrid method, a complex antenna is approximated using linear interpolation to determine field values from a finite set of measured or calculated points. The antenna is treated as a point source with a complex pattern. The antenna fields are traced through the rest of the system to determine the effect of the system on the antenna pattern.

In a third hybrid method, the GTD code is used to solve for a modified impedance matrix for the MOM solution. In effect, the GTD solution becomes the Green's function for the problem.[40]

Table VIII lists some available hybrid codes. These are described in more detail in Section III.

Table VIII. Common Hybrid Codes

Name of code	Source	Approx. Cost	Public Domain Software?	Type of code
GEMACS	Rome AFB	$250	yes	MOM and GTD code
BSC/NEC	Ohio State/ Lawrence Livermore Labs	see separate code costs	yes	MOM and UTD
MOM/UTD Code	Sandia National Laboratories	-	no	MOM and UTD
MOM/UTD Code	University of Dayton	-	no	MOM and UTD
GMULT Code	Georgia Tech Research Institute	distribution cost	DoD	MOM and PO

More information regarding each of these codes is presented in Section III. Many other companies, universities, and government labs also have developed hybrid codes that are either proprietary or developmental. Table IX gives a listing of some of these.

Table IX. Institutions with Hybrid Codes

Institution	Location
McDonnell Douglas Research Labs	St. Louis, MO
Jet Propulsion Laboratory	Pasadena, CA

F. Reflector Design Codes

Reflector antenna codes in general utilize high frequency solution techniques and so cannot model reflectors less than a few wavelengths in diameter.

Many reflector design codes break up the current and the far-zone scattered field into their rectangular components. Subtraction of the radial component is assumed. They then use the physical optics approximation, where the calculated current is the current that would be induced on an

infinite conducting plane under illumination by an infinite plane wave. This approximation ignores any reflections that might take place at the edges of the reflector. Also, the currents do not satisfy the edge conditions, which require the normal component of current to be zero and the tangential component to be singular at an edge.[41] This approximation in general gives good results for the main beam region and the near side lobes.

The Cartesian decomposition and physical optics approximation is suitable for focused reflectors, but not as good for defocused reflectors such as hyperbolic sub reflectors in Cassegrain systems.[41] The GTD method is more suitable for that type of problem.[42]

Another HF approach used for modeling reflectors is spherical wave theory. This approach involves the use of spherical wave harmonics. The radiation pattern is expanded into a series of spherical wave harmonics. Spherical wave theory generally yields more accurate results than GO/GTD, but requires more computation time.[41]

G. Optical Ray Tracing Codes

There are several optical ray tracing codes available that can be applied to antenna modeling at high frequencies. Some of these can handle diffraction. They can be used for some simple systems such as modeling a dielectric lens for antennas.

H. RCS Codes

Aerospace engineers who design low observable vehicles rely on RCS (Radar Cross Section) codes as a design tool particularly to eliminate hot spots. Intelligence analysts rely on RCS codes to estimate the signature of foreign targets that are unavailable for RCS measurement. Material engineers rely on RCS codes to predict material performance. And electronic engineers rely on RCS codes to predict where fuzziness will occur for missile engagement scenarios.

Traditionally, estimates of radar signature of aircraft designs were obtained by building scaled models and testing them at radar ranges. This can be prohibitively expensive and time-consuming. Considerable effort has been put into RCS code development over the past few years. This has been fueled partially by the stealth aircraft development programs. RCS codes use the same techniques as antenna modeling codes. However, most of these codes do not allow for antenna analysis. It would be fairly easy for the code developer to adapt an RCS code to an antenna code.

Reference 72 gives a listing of several public domain and company proprietary RCS codes. These codes can be broken up into high frequency (HF) and low frequency (LF) codes.

For the HF codes, the dimensions of the objects are on the order of several wavelengths. For the low frequency codes, the dimensions are on the order of a wavelength. The HF codes generally use the Physical Theory of Diffraction (PTD) or the Geometrical Theory of Diffraction (GTD). One of the better known public domain codes is MISCAT[43]. MISCAT was started in the 1960's by the Northrop corporation. It can accept cylinders, spheres, and other primitive geometries along with flat plates. Another popular public domain RCS code is McPTD[44]. Developed by DEMACO Corporation in the early 1990's, this code can accept curved surfaces in the IGES format. It can predict both near- and far-field RCS. Most of the RCS codes for LF are based on a MOM formulation.

The computer-aided design (CAD) software is an integral part of the RCS computation. A good CAD program should be able to work with several geometry types such as flat plates, curved surfaces, cylinders, ellipsoids, ogives, cones, spheres, boxes, corner reflectors, bodies of revolution, and solids. The Initial Graphics Exchanges Specifications (IGES) is a standard for storage of geometry databases.[45] A standard is important because it allows different CAD programs to share the same geometry. ACAD[46] is one CAD code which can work with flat and curved surfaces in the IGES format. BRLCAD is another commonly used CAD package in the public domain.[47]

RCS codes are required to model complex vehicle geometries ranging from a few wavelengths in size to a few thousand wavelengths. Both LF and HF codes are usually required to cover the design space. Analyses of these geometries severely stresses the capability of CRAY supercomputers, and are beginning to be addressed by massively parallel supercomputers such as the Connection Machine and the Intel i/PSC860.

Researchers at the McDonnell Douglas Corporation use the Triangular Surface Patch (TSP) Code for MOM modeling and the CADDSCAT code which uses the physical theory of diffraction (PTD) for HF modeling.[48] They use a CAD system which uses the IGES standard. The TSP code has been modified to allow material treatments on rectangular plates (PLATE3D code). Their CLOAK code is another modification of the TSP code which has an impedance boundary condition (IBC) option. This code uses unique basis functions to achieve superior accuracy with only 4 unknowns per wavelength. Typical MOM codes require as many as 15 to 20 unknowns per wavelength.

The CADDSCAT PTD code uses a proprietary ribbon algorithm for large bodies which allows for a 40 to 1 speed improvement over Gaussian

quadrature surface integration. Using the Intel supercomputer at 4 GFlops and with 40 GBytes of memory, they can routinely perform an MOM analysis with 50,000 unknowns.

General Dynamics has developed a physical optics code for RCS analysis called VISAGE which takes advantage of an advanced graphics environment such as the Silicon Graphics Iris 4D Series workstation.[49] They use the aperture field method for the PO calculations which is preferable over the old current distribution method and faceting approach or the method of parametric patches and shadowing. The graphics workstation is capable of visualizing and computing RCS of very complex structures in a minimal amount of time. Structures with up to 41,000 facets have been analyzed. One potential problem with this type of analysis is that the developer is limited in resolution to the screen size which has 1024 x 1024 pixels. They use the ACAD (advanced computer aided design) program which has been designated as the standard geometry generation code by the EMCC.

Syracuse Research Corporation uses a RCS prediction package called SRCRCS with an accompanying CAD package called SCAMP.[50] Theoretical predictions in SRCRCS are performed using the theories of physical optics (PO) and the physical theory of diffraction (PTD). This code implements HF solutions for curvilinear patches to reduce error due to the staircasing effect. They also have an MOM code for LF work. This uses an EFIE formulation based on curvilinear patch subdomains. With this type of formulation, fewer elements are needed and greater accuracy is achieved.

Researchers at Rockwell International use a finite-volume time-domain (FVTD) approach which uses curvilinear body-fitted coordinates.[51,52] It allows the entire configuration to be divided into zones of different electromagnetic properties and curvilinear grids to be set up in every zone with the optimal grid density determined by local material properties. A perfectly conducting 3D object $250\lambda \times 150\lambda \times 25\lambda$ in size at one scattering angle using a FVTD approach would require on the order of 1 billion grid cells and 100 hours of computing time on an 8 processor machine equipped with sufficient memory and capable of sustaining continuously the speed of 2 gigaflops. They also use a GTD/PTD code for high frequency work and for initial design studies. Then they switch to either their FVTD code or their MOM code called AIM. The AIM code uses a CFIE approach and can handle dielectric, magnetic, and lossy material. They use a Silicon Graphics machine for their GTD code.

The Electromagnetic Code Consortium (EMCC) was established in 1987 by the Tri-Services and NASA to consolidate RCS code development. The objective was to advance the state-of-the-art in basic EM scattering research by determining the current level of general development and suggesting avenues for further advancement. The consortium develops guidelines to assure compatibility of developed codes and sets benchmark problems by which the codes' performances can be compared. Distribution of codes and documentation as well as training will be provided by the consortium participants.

Currently one of the EMCC DARPA projects is to utilize parallel processing for RCS analysis. Their goal is to model in one day's computer time a large aircraft at 1 GHz.

Alex Woo at Ames Research Center, Moffett Field, CA 94035-1000, can be contacted for more information on the EMCC. Some member of the EMCC steering group are

NASA Ames Research Center
US Army Missile and Space Intelligence Center
US Naval Air Warfare Center
University of Michigan

Some of the EMCC members are

Northrop
Rockwell International
Syracuse Research
Lincoln Labs
Grumman
McDonnell Douglas
General Dynamics
Boeing
GE
Lockheed
Ohio State University
University of Illinois
Auburn University
University of Dayton
Northwestern University
Lawrence Livermore National Laboratory
Los Alamos
Sandia
JPL

III. AVAILABLE COMPUTER CODES

The following is a description of some commonly available antenna modeling computer codes. Many other companies, universities, and government labs have developed modeling codes, but these are either proprietary or developmental in nature. Tables II, V, VII, and IX have listed some of these institutions. Many of these institutions' codes are simply a standard code with some modifications added. There are also many EM codes available for RCS analysis that are not listed.

To help alleviate the problem of software distribution in numerical electromagnetics research, a server has recently been established at JPL (Jet Propulsion Laboratory). This server, called EMLIB, is maintained by volunteers who actively solicit and catalogue software. The software will be written in standard languages and will be available for public domain distribution. It can be accessed through electronic mail and anonymous ftp servers. This server is similar to the NETLIB server, a source of current numerical analysis software maintained by workers at AT&T and Oak Ridge National Lab.

EMLIB can be accessed at the address, microwave.jpl.nasa.gov. The IP address is 128.149.76.31. The email address is emstaff@microwave.jpl.nasa.gov.

The IEEE Antennas & Propagation Magazine has a monthly column on EM software. Conferences and journals are also a good source of information on new EM software. The IEEE Antennas and Propagation Society International Symposium usually held in the summer each year has many sessions devoted to antenna modeling. The Applied Computational Electromagnetics Society (ACES) has a yearly conference held in the spring.

A. Method of Moments (MOM) Codes

1. NEC (Numerical Electromagnetics Code)

The NEC code involves a moment method model for thin wires based on point matching and sinusoidal-spline basis functions. The NEC algorithm, which has been in use since about 1978, has recently been modified to improve the accuracy for wires with discontinuous radii and tightly coupled junctions and to avoid loss of precision in modeling electrically small antennas.[53] The NEC code uses the

electric field integral equation (EFIE) to model wire grids. Two approximation options are available in NEC, the thin-wire kernel and the extended thin wire kernel. Using segments larger than $\lambda/10$ is not recommended. Segments $\lambda/20$ or less are recommended in critical areas of the antenna. The ratio of wire radius to segment length should be kept small. The NEC User's Guide[54] recommends that the ratio of $2\pi a/\lambda$, where a is the wire radius, be much less than one.

NEC includes a patch option which uses the magnetic field integral equation (MFIE) to model surfaces. This option is restricted to closed surfaces with nonvanishing volume such as a box or sphere. For modeling surface patches, a minimum of about 25 patches should be used per square wavelength, or a maximum size for an individual patch of about 0.04 square wavelengths.

The NEC model can include nonradiating networks and transmission lines, perfect and imperfect conductors, lumped element loading, and ground planes. The ground planes may be perfectly or imperfectly conducting. Excitation may be via an applied voltage source or incident plane wave.[55]

The current NEC code version is NEC-2. There is also another version called NEC-3 which can be used for non-perfect grounds and buried wires. This code is capable of modeling ground screens and other antennas near to or buried in the ground.[56] NEC-3 runs slower than NEC-2 and so is not recommended except for those special cases. When using NEC-3 a special program, Sommtxd, needs to be run to add the relative permittivity (ε_r), conductivity, and frequency to the NEC-2 input.

The arrays of NEC-2 can be easily adjusted up or down so that more segments can be modeled on machines with more memory.

NEC-2 calculates the input impedance of the antenna, the efficiency, the currents on all the wire segments, the near and far field electric and magnetic fields, and the power gain in dB.

Table X shows the ratio of computer memory requirements for the NEC code versus number of unknowns. This is for the case of the NEC-2 code run on a Mac IIfx (40 MHz) computer using MPW (Microsoft Programmers Workshop) FORTRAN. The run times will increase if virtual memory is used.

TABLE X. Number of Unknowns versus Computer Requirements for NEC Computer Code

No. of Unknowns	Computer RAM Memory Required (MBytes)	Solution Time (hours)
600	7.4	-
810	13.1	7
950	16.9	-
1000	18.6	-

The NEC code and documentation is available through COSMIC for $1700 at the following address:

COSMIC
The University of Georgia
382 East Broad Street
Athens, Georgia, 30602
FAX 404-542-4807
404-542-3265

It is also available from Jerry Burke at Lawrence Livermore Laboratory at the following address:

Jerry Burke, L-156
Lawrence Livermore National Laboratory
E.E. Dept., Engineering Research Division
P.O. Box 808
Livermore, CA 94550
(510) 422-8414, FAX (510) 422-3013

This is the latest version of the code which is still under development and is free to government labs. It is available to DoD contractors and others at a distribution cost of $850 for the DEC-VAX version or $250 for the MacIntosh version. This price includes a graphics data previewer and documentation.

The Applied Computational Electromagnetics Society (ACES) offers a software package called NEEDS2 which is a set of programs for the PC computer that includes NEC-2, MININEC, the ANTMAT broadband antenna matching program, and two other small

programs for plotting and data entry for NEC. They also offer a PC version of the Ohio State ESP code. ACES holds a yearly symposium and publishes a journal and newsletter on electromagnetics and computer modeling. More information can be obtained from:

Richard Adler
Applied Computational Electromagnetics Society (ACES)
Code EC/AB
Naval Postgraduate School
Monterey, CA 93943

NEC-3 is treated as Military critical technology and its distribution is restricted to DoD agencies or contractors who need the code to work on a DoD contract.

MacVerify (described in the graphics codes section below) is a geometry pre-processor for NEC and GEMACS which converts a data file into a 3-dimensional rotatable and scalable picture. This allows the user to determine if the structure he has built is accurate. It has the option of showing the structure as lines or solids. Other 3-dimensional graphics packages (listed below) are available but the NEC input file must be converted to a usable form.

For plotting NEC output the MacIntosh Kaleidagraph plotting software (Synergy Software, Reading, Pa., 19606, (215) 779-0522) was found to be convenient. The NEC output was easily imported into it and parts of the output could be plotted separately in linear or polar plots.

2. MININEC

MININEC is the PC version of the NEC code. Only wire modeling is allowed for this code, and it can only handle a few hundred unknowns.[55]

The public domain version of MININEC is free but is not very user friendly. The written report, called The New MININEC (Version 3): A Mini-Electromagnetics Code, is by J.C. Logan and J. W. Rockway. NOSC Technical Document 938, September 1986. An enhanced version of MININEC and documentation by the original authors is available through Artech House, Inc., 685 Canton Street, Norwood, MA 02062 (1988). A more user-friendly version of MININEC is available from Brian Beezley, 507 1/2 Taylor Street, Vista, California 92084, (619) 945-9824 at a cost of $300. A version of MININEC is also available from ACES as described above.

3. ESP4

ESP4, the Electromagnetic Surface Patch Code, is a method of moments code useful for defining antenna parameters and scattering from small objects. This code is most useful for analysis of antennas and scatterers no bigger than a few wavelengths. The ESP4 code was developed under government contract by Dr. E. H. Newman and several other researchers at the ElectroScience Laboratory at Ohio State University. It can model wire grids and surface patches. Because the surface patch modeling is based on the EFIE and not the MFIE, the surfaces do not have to be enclosed as in the NEC code, so open surfaces such as plates, corner reflectors, fins or wings, and boxes with holes can be modeled.[11]

Perfectly conducting or thin dielectric polygonal plates can be modeled, along with thin wires, wire/plate junctions, and plate/plate junctions. Excitation may be either by a delta-gap voltage generator or by a plane wave. The thin wires may have finite conductivity and contain lumped loads. The code computes the current distribution, input impedance, radiation efficiency, mutual coupling, near or far field gain patterns (both polarizations) and near or far field scattering patterns (full scattering matrix).[11]

Only plates with four or more corners can be modeled, however, triangular patches can be simulated by making one of the four corners in the center of the longest side of the triangle.

This code is very user-friendly and comes with a good user's manual. The program automatically segments plates and wires specified by the input.

The latest version of the code (August 1988) allows for thin dielectric plates and near field radiation and scattering patterns.

The code can be dimensioned for the number of unknowns the computer memory will allow. The source code is provided so the program will run on any machine with Fortran 77.

The ESP4 code is available at a distribution cost of $250 from:

The Ohio State University
ElectroScience Laboratory
1320 Kinnear Road
Columbus, Ohio 43212

The ESP4 code, as well as the other Ohio State codes, have a graphics capability that needs to run on a machine with GKS (Graphics Kernel System). GKS is available on the NRL RCD VAX but

is not completely compatible with the Ohio State graphics codes, so getting the graphics to work for the Ohio State codes can be a major project. Another option is to modify the BSC input for use in the Super3D code (described below) on the MacIntosh computer. This code allows complete rotational freedom and scaling and an easy printout. Ideally, a Fortran or PASCAL program can be written to automatically convert the BSC code input to a Super3D file.

4. AWAS (Analysis of Wire Antennas and Scatterers)

This is a general purpose MOM code, similar to MININEC, for analysis of wire antennas and scatterers. It is written for an IBM PC computer. It has an excellent user's manual, is easy to use, and can do some circuit analysis.

It is severely limited in that only 150 unknowns are allowed. No source code is available so it cannot be enlarged. Unlike the NEC and ESP4 codes, only wire analysis is performed. The graphics are in general fairly good, however, getting a hard copy can be a problem unless a PC plotter is available.

AWAS was developed by A. R. Djordjevic, M. B. Bazdar, G. M. Vitosevic, T.K. Sarkar, and R. F. Harrington, and is available from Artech House Publishers in Boston.

AWAS has been extended for 500 unknowns for an OS-2 operating system. It also handles bodies of revolution. This sells for $3000.00. A.R. Djordjevic in Yugoslavia is the developer and will extend AWAS to any size for a fee. Prof. Harrington, of Syracuse University, Syracuse New York 13210, (315) 443-4391, handles the marketing for this product in the US.

5. SWJ3D (Surface wire junction 3D)

This is a MOM code, developed at the University of Illinois, which uses the electric field integral equation (EFIE). The system can be excited with a plane wave, dipole or voltage source. The Radar Cross Section (RCS), near- and far-fields, and the input impedances can be calculated.

With this program, the surfaces are split up into a wire grid or triangular patches. Various basis functions are used to describe the currents on the patches. The wire segments use pulse basis functions. The Galerkin method, a procedure for approximating analytical operator equations by matrix equations, is used to solve

the equations. Because the EFIE equation is used, the surfaces do not need to be enclosed. Using $\lambda/10$ is a rule of thumb for the section sizes. This decreases to $\lambda/15$ for computing the near fields accurately.

The advantage of this code over other MOM codes is that it is interfaced to a mesh generator. This enables complex structures to be easily modeled. The structure is developed in PATRAN, a mesh and finite element generator which is used with the popular NASTRAN finite element code. PATRAN can generate a surface mesh or a volume mesh for finite elements. Another program is then used to convert the PATRAN output into an input file for their code.

At the Univ. of Illinois, the Apollo 3500 series system, which is an HP workstation, is used to generate the PATRAN mesh. It uses the Domain operating system with standard PATRAN. After using PATRAN, the output is transferred to a CONVEX (DECStation) to run the main program. Using 1800 unknowns, enough to model the tank shown in Figure 6 with a 300 MHz antenna mounted, takes about 2-3 hours to compute with no other users. For the output plots, Kaleidagraph on the MacIntosh is used. An experienced PATRAN user would need approximately 1 hour to mesh a tank including the gun, turret, and 300 MHz antenna. The DEC station can handle up to 2000 unknowns. After that a CRAY is needed.

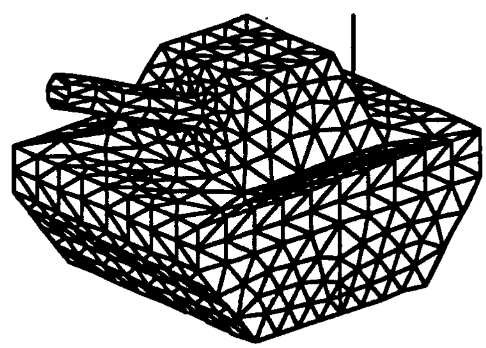


Figure 6. Tank meshed for antenna analysis at 300 MHz.[57]

A vectorized version that runs on a YMP CRAY is currently available and can run up to 20,000 unknowns. An out-of-core solver for the CRAY is desirable but is not currently available. Using the Connection machine, or a machine with similar parallel processing architecture, is also desirable but the Univ. of Illinois codes are, as yet, not developed for this type of machine. Using 2000 unknowns is

the maximum for a DEC 5000 workstation and takes about 3 hours to solve.

The SWJ3D program is still under development. It does not model infinite ground planes (like the NEC program), and they are currently changing the code to handle dielectrics using the tangential boundary condition. The SWJ3D program can only do voltage sources, not patches or slot antennas. A magnetic current source is needed for those, and the code is currently being updated to do this.

The SWJ3D code has been compared with published data and good agreement is obtained except for the imaginary part of the impedance. This is because of the way the voltage source is modeled as a deltagap, or delta function source. This disagreement affects the matching network but does not affect the far-field calculations.

The SWJ3D program was compared to NEC and good results were obtained except when distributed loading of the antennas was used. The SWJ3D program compared well to other published results, so apparently the NEC program cannot handle this type of problem. Another problem the researchers at the Univ. of Illinois had with NEC was with using too thin patches. In NEC, the patches need a finite thickness. The patches in SWJ3D are infinitesimal.

Much of the work at the University of Illinois involves design studies to reduce RCS. They can use a perturbation analysis where things are modeled separately and then the patterns are combined.

The SWJ3D code and the FE and FDTD codes from the University of Illinois were all developed by professors and students. Each of the codes is priced at $30,000. This includes the source code and user's manual but only limited support by the University of Illinois staff. These codes can be obtained by contacting:

Dr. Raj Mittra
Electromagnetics Laboratory
Electrical Engineering Department
466 Everitt Laboratory
1406 W. Green St.
Urbana, IL 61801-2991
University of Illinois
217-333-1202, secretary: 217-333-1200
FAX: 217-333-8986

6. Patch Code

The EPATCH code (also known as the Patch code) is another MOM code similar to NEC. It uses EFIE and piecewise linear basis functions. The EPATCH code was developed initially at the University of Mississippi. Dr. Edmund K. Miller at Los Alamos National Laboratory is a user of this code.

Documentation for the Patch code is available from:

1. Patch Code User's Manual
   Johnson, Wilton, Sharp
   1988 Sandia Report #D-87-2991

2. Patch Code Report
   User's Guide (Part 3)
   Lincoln Labs Technical Report #785
   Numerical Modeling of RCS and Antenna Problems
   1987, S. Lee

3. PATCH code
   MOM 3-D Method of Moments Code
   Theory Manual
   Rao, Wilton, Glisson
   Report for NASA by Lockheed
   NASA report #189594, March 1992
   author: John Shaeffer 404-952-3678

B. Finite Element (FE) Codes

1. EMAS

EMAS (Electro Magnetic Analysis System) is a general purpose computer program which analyzes electromagnetic fields in three dimensions using the finite element method. It is coupled with a graphical pre/postprocessor, MSC/XL, for model generation and results interpretation.[5] Applying Maxwell's equations to finite elements, EMAS can model electrostatics, magnetostatics, eddy currents, charge relaxation, and wave propagation. Static and transient analysis can be done, and conformal grids can be used.

The latest version of EMAS (released in the spring of 1992) can handle absorbing boundary conditions on boundary elements and so

is suitable for antenna analysis. A second order boundary condition is used which is designed for an incident spherical wavefront. The boundary can in general be placed a few wavelengths from the antenna surface. This version also allows for real and complex material properties and unlimited problem size. Practically, though, for overnight runs, 4,000 unknowns is the limit for a workstation class of machine. This will be higher for mainframes and supercomputers. Problems with up to 50,000 unknowns have been run by the MacNeal-Schwendler Corporation (MSC).

Coarser element sizes can be used farther away from the sources, but there will still be a problem in the amount of computer time and memory needed for large antenna problems. Up to $\lambda/60$ segmentation can be needed to model critical areas, and this cell density requires 3600 unknowns just to model an area $1\lambda \times 1\lambda$ in size.

EMAS is available from MSC, Mount Laurel, New Jersey, (609) 778-3733. EMAS runs on workstation class computers from DEC, HP/Apollo, and Sun and mainframe type computers from Convex, Dec, HP, IBM and Cray. It is leased to a site for a cost of $2000/month. It is currently available for use at NRL in the Research Computational Division (RCD) of NRL on a SUN computer. This availability may change, however, in the next year, and there is a chance EMAS will not be available after that.

MacNeal-Schwender has plans to split up the EMAS code into codes specific to certain problems. One of these new codes will be an antenna modeling code. The inputs and outputs of the codes will be specifically tailored to antenna modeling.

2. University of Illinois FE code

The University of Illinois has a FE code. The FE code, as it exists now, can only be used for scattering problems and needs to be updated. Like their MOM code, SWJ3D, it uses the PATRAN mesh generator.

The FE code is set up exactly like their FDTD code but handles the problem in the frequency domain, not the time domain. The FE code generates a sparse matrix and this matrix must be inverted. The inversion can be difficult and the inverted matrix is no longer sparse.

The FE code is available from the University of Illinois as described above for $30K. This includes a manual and the source code but not any time from them to help set up the code or use it.

C. Finite Difference Time Domain (FDTD) Codes

1. TSAR

The TSAR (Temporal Scattering and Response) EM Code was developed at Lawrence Livermore National Laboratory by Dr. Scott Ray and Mr. Steve Pennock. The TSAR code actually consists of a family of related codes that have been designed to work together to provide users with a practical way to set up, run, and interpret the results from complex 3-D FDTD EM simulations.[58] Development of the software began in 1987 and limited distribution of the code began in 1991.

The core physics package of TSAR is a finite-difference time-domain (FDTD) code for simulating the interactions of electromagnetic waves with linear materials. A body under study can be represented as a three-dimensional rectangular, Cartesian grid of materials with arbitrary linear properties. The grid can be stimulated in a number of ways including incident plane waves, voltage generators, and arbitrary incident fields. The grid can be terminated by application of various boundary conditions including free-space radiation, electric conductor, or magnetic conductor.

The TSAR code uses the MGED CAD/CAM package based on solid modeling techniques. It is used to create, edit, and store a geometric description of the object being analyzed. This code is part of the BRL-CAD package which was developed by the US Army at the Ballistics Research Laboratory in Aberdeen MD. This code is distributed freely to US organizations.

The package called ANASTASIA generates three-dimensional finite-difference meshes automatically from a geometric description of the problem generated by MGED. The meshes are examined by IMAGE, which verifies the problem grid, finds bugs and design flaws, and allows visualization of the mesh.[59]

There are five possible types of input to TSAR: the compile time parameters, the run-time input file, the grid file, the user-defined pulse files, and the incident field functions. The last two of these are optional. TSAR produces an input verification file that also reports on TSAR's progress, a grid check verification file, an

incident pulse shape file, and a file containing the data recorded starting at any time step, ending at any time step, and sampled at any fixed interval.

There are also several post-processing codes as part of the TSAR code. One of these is an interactive signal processing code which allows data to be scaled, shifted, and Fourier transformed. The frequency domain solution to the problem can be obtained by stimulating the grid with an impulse function and doing Fourier transforms on the time solution at each grid point.

The TSAR code uses three different field projection algorithms for modeling radiation and scattering problems:

A. time domain extrapolation to points in the far field,
B. time domain extrapolation to points in the near field,
C. frequency domain extrapolation of the EM field to far field pattern plots.

At Lawrence Livermore, the TSAR code runs on an IBM workstation. A problem with 700,000 cells will run overnight. They regularly do runs with up to 1,000,000 cells.

Modeling a sphere, the researchers obtained reasonable results using $\lambda/40$ segmentation for moderate frequencies and curvatures. In general, because of the staircased representation of curved surfaces, poor high frequency behavior is expected.

ESTSC, at the following address, distributes the code and user's manual.

Energy Science and Technology Software Center (ESTSC)
P.O. Box 1020
Oakridge, Tenn. 37831
615-576-8403, 2606

The cost is $140.00 for a SUN version, $500.00 for a Mainframe version with a Unix operating system, and $1200 for a Cray1 version. Work is also currently being done to port the code to parallel processing machines. The programming languages used are Fortran 77 and C, with the core physics program written in Fortran. The source code is provided.

2. University of Illinois FDTD code

The University of Illinois also has a finite difference time domain (FDTD) code. Like their MOM code, SWJ3D, it uses a PATRAN mesh generator.

The FDTD code currently uses a Cartesian system and they are trying to update it to do a conformal grid so that curved surfaces can be modeled without a staircasing effect. One main difficulty in implementing conformal grids is developing an algorithm for determining who the nearest neighbor cells for each individual cell are. The FDTD code is like the FE code except that the matrix does not need to be inverted and so the solve time is proportional to N and not N^2. With this code, each cell calculates a steady state distribution of fields with respect to its nearest neighbors. This process is repeated over and over again until the fields reach steady state. Sometimes several thousand steps must be made. This code is well suited for the Connection machine. It doesn't handle dispersive medium.

Dr. Mittra at the University of Illinois recommends the MOM codes over the FDTD and FE codes except when using dielectric materials.

The code currently doesn't include a variable (non-uniform and non-orthogonal) mesh. It runs on a CRAY and is vectorized. Dr. Mittra also mentioned that a finer mesh than the MOM codes, on the order of $\lambda/60$, is needed to get reasonable results.

The FDTD code is available from the University of Illinois as described above for $30K. This includes a manual and the source code but not any time from them to help set up the code or use it.

3. EMDS Code

This is a system of codes built around the FDTD method developed by Dr. Alan Taflove and his colleagues at Northwestern University. It uses second order radiation boundary conditions. It has been optimized for use on Cray Research systems and includes a graphical interactive user interface which uses the industry standard ACAD system and a 3D postprocessing program. ACAD can import IGES files from other CAD packages and is capable of full curvilinear mesh generation.

Currently the program only utilizes one processor, though the Cray machines have up to 16 processors. They have run the code at

a maximum speed of 1.6 Gflops. The Cray machine they are using does not have virtual memory, however, it has 4-8 GWords of real memory and is capable of running billions of unknowns. One benchmark program they have run involves 9.8 million unknowns. This problem took 23 seconds/time step. FDTD problems can take several thousand time steps to stabilize.

They are interested in running sample problems at no cost. A problem would be sent to them and they would run it and make a video of the output. They would use the sample problem for marketing purposes.

Currently, EMDS is set up for scattering and RCS calculations, however, they are modifying the code for antenna problems. A license for one year will cost $80-$160K. It is available from:

Cray Research, Inc.
655-E Lone Oak Drive
Eagan, MN 55121
Attn: John Ahnert
(612) 683-3630/ (214) 450-9500

D. Geometric Theory of Diffraction (GTD) and Other High Frequency Codes

1. BSC (Basic Scattering Code)

The Basic Scattering Code (BSC) is a GTD code which uses combinations of flat plates, elliptic cylinders, composite cone frustrums, and composite ellipsoids to simulate scattering structures. It has been used to simulate the scattering from the superstructure of a ship, the body of a truck or tank, the fuselage, wings, and stores of an aircraft, or the living quarters of a space station using perfectly conducting plates and cylinders. The dielectric capability can be used as an isolated thin slab which can simulate a radome or windshield, or it can be mounted on a perfectly conducting plate in order to simulate composite material or an absorber-coated ground plane, or as a semi-infinite half space to simulate the earth. This capability is not complete but future versions of the code will improve on it.[37]

The BSC code uses the UTD approach. Components of the diffracted fields are found using the UTD solutions in terms of the individual rays. These are then summed with the geometrical optics terms in the far zone of the scattering centers. The rays from a given scatterer tend to interact with other structures causing various higher-order terms. The various possible combinations of rays that interact between scatterers can be determined. Only the dominant terms are included. Thus, only the important scattering components are included and the higher order terms neglected. This allows for an accurate and efficient computer code.[37]

The plates in the model should have edges at least a wavelength long. If a dielectric slab is used the source must be at least a wavelength from the surface, and the incident field should not strike the slab too close to grazing. In addition, each antenna element should be at least a wavelength from all edges. (For engineering purposes, this can be reduced to a quarter wavelength.)

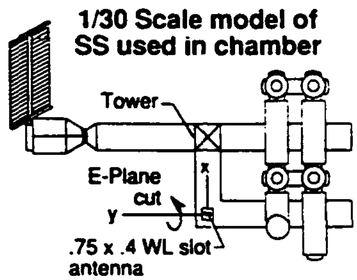
Antennas can be represented as infinitesimal Green's functions. Also, there are six built-in antenna types, or a linear interpolation of table look-up data can be used. There is also an interface for using MOM code input.[37] With this option, a wire antenna can be modeled using a MOM code like NEC, and the resulting currents on the wire segments found. The currents and wire locations are then input directly into the BSC code, along with any other added plates. This is a nice option which allows for accurate high frequency modeling of complicated antenna types along with their surroundings. An application of this for a quadrifilar helical antenna on a spacecraft is presented in the Section IV of this report.

The BSC code has an excellent users manual and is easy to use. It can handle different dielectric constants for plates and also plates with several layers of different dielectrics. It does not model dielectrics on anything other than a flat plate. One limitation is that antennas can't be mounted on curved surfaces. The NEWAIR aircraft code can be used for those types of problems.

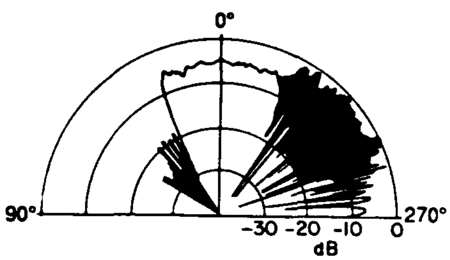
This code does not compute the input impedance or the power gain in dB. It outputs the relative magnitude of the fields in dB which is dependent on the input voltage. The input voltage can be adjusted so that the magnitude of the fields and the power gain matches, but this is assuming a good estimate of the power gain, or at least the peak power gain, can be obtained. The NEC code can be used to model part of the antenna and its output used to get an estimate. It would be fairly easy to modify the BSC code to integrate

the total power over the whole field, however, this would entail calculating the fields over the whole solid sphere. Normally, the fields are only calculated over a cross section specified by the user, so this would take considerably more time to compute.

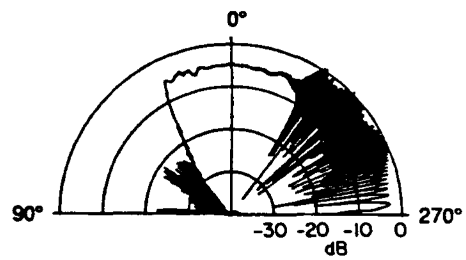
Researchers at Ohio State University have used the BSC code to model a section of the NASA Space Station and have compared their results to data from a scale model.[37] Figure 7 shows the model and the results.



(a)



(b)



(c)

Figure 7. Comparison of measured versus calculated data of antenna patterns from a slot antenna on a section of a scale model of the NASA space station, (a) Scale model, (b) Measure E-plane pattern, (c) E-plane pattern calculated with BSC.

The BSC code has a graphics capability but needs to be run on a VAX with GKS graphics. GKS is available on the RCD VAX but is not completely compatible with the BSC graphics code. The BSC input can also be modified for use in the Super3D code. This code then allows

complete rotational freedom and scaling and an easy printout. Ideally, a Fortran or PASCAL program can be written to automatically convert the BSC code input to a Super3D file.

The code can be dimensioned for the number of unknowns the computer memory will allow. The source code is provided so the program will run on any machine with Fortran 77.

The BSC code and user's guide is available at a distribution cost of $250 from:

The Ohio State University
ElectroScience Laboratory
1320 Kinnear Road
Columbus, Ohio 43212

2. NEWAIR - Aircraft Code

This is a GTD code, developed at Ohio State University, similar to the BSC code except that antennas can be mounted on curved surfaces.[60] It is specifically designed for aircraft and does not have all the capabilities of the BSC code. The antenna must be mounted on a composite ellipsoid. Unfortunately, more than one ellipsoid cannot be used and the only other components are flat plats. A maximum of 25 plates with up to six corners each can be modeled. This can be increased if the dimensions inside the code are increased and a computer with enough RAM memory is used.

The program automatically attaches the plates used as wings to the fuselage if a good estimate of the attachment location is given. The program can give erroneous and unsymmetrical results if the estimate is not accurate enough, though. The program cannot handle dielectric material.

Flat plates are needed to model a propeller as there are no options for using cylinders. The user's manual gives an example where two flat plate propellers in various arc locations are modeled and the results combined to give the variation in the pattern as the propeller spins.

This code cannot calculate impedances and only a relative magnitude of the fields is calculated which is dependent on the input voltage. The input voltage can be adjusted so that the magnitude of the fields and the power gain matches, but this is assuming a good estimate of the power gain, or at least the peak power gain, can be obtained. The NEC code can be used to model part of the antenna

and its output used to get an estimate. It would be fairly easy to modify the NEWAIR code to integrate the total power over the whole field, however, this would entail calculating the fields over the whole solid sphere. Normally, the fields are only calculated over a cross section specified by the user, so this would take considerably more time to compute.

The program is easy to use and comes with a user's manual containing several examples. It can be dimensioned for the number of unknowns the computer memory will allow. The source code is provided so the program will run on any machine with Fortran 77. The program needs to be modified to use an input file instead of interactive input.

It would be convenient if the NEWAIR code and BSC code were combined to form one code as each code has some limitations that the other code can handle.

This code uses a modification of the Ohio State BSC graphics code, which is not easily implemented. It is also possible to convert the input and use the Super3D program for graphics.

The NEWAIR code and user's guide is available at a distribution cost of $250 from the Ohio State University ElectroScience Laboratory.

3. GMULT

This code, developed at the Georgia Tech Research Institute (GTRI), is primarily used for computing microwave antenna patterns in the presence of scatterers such as a Navy shipboard antenna through masts or a space station.[76] The frequency range is 500 MHz and above. Small antennas can be used or large reflectors and phased arrays. This is because the far-field pattern phase and amplitude of the antenna alone is entered for the antenna. From this the near-field amplitude and phase is derived. Physical optics is used to compute the near-field scattering due to various structures and a new far-field pattern is computed taking this into account.

GTRI has plans to incorporate GTD into their model. The GTD method is needed mainly for accurately modeling low side lobes.

Another GTRI program, called GCUPL, is used in conjunction with GMULT and computes in-band and out-of-band coupling between antennas in the near field as well as far-field power densities.

Specifically, GMULT uses a spectral analysis technique. It computes the spherical angular functions (SAFs) for directive antennas. The SAF for a given antenna is directly proportional to the complex two-dimensional far-field pattern of the operating antenna. The SAF near-field scattering analysis technique is based on convolution integrals involving the SAF for each antenna and each scattering obstacle. If there is more than one scattering obstacle nearby, the resultant scattered SAF for the set is determined by the "marching in range method".

These codes were developed for the Navy and can be distributed to Navy facilities free of charge. The code can run on a PC with 8 MBytes of memory. GTRI contact is Barry Cown at (404) 894-3135. The technical monitor for the project at NAVSEA is Vinh Trinh at 703-602-7996/7348. He is using the code for radar analysis.

E. Hybrid Codes

1. GEMACS

The General Electromagnetic Model for the Analysis of Complex Systems (GEMACS) is a continually evolving computer program developed by the Air Force for analysis of electromagnetic field phenomena. Its applications are for antenna performance, EM scattering and radiation, EMP, EMC, jamming susceptibility, ECM and ECCM, and radar cross section.[9,73]

This code is a hybrid code that uses MOM, finite-difference modeling, and the GTD methods together. The method of moments is used for the resonant frequency region. The GTD method is used for structures that are very large compared to the wavelength. And the finite difference method is used for the interior of the structure.[9]

In the hybridization technique, the exterior problem interaction matrix is calculated using MOM/GTD after the method of Thiele[61]. The interior problem interaction matrix is calculated using FD. The total problem solution is found by using the Householder Method of Modified Matrices to link the separate solutions at their common interfaces.[62] GEMACS grew out of the EMCAP MOM/GTD hybrid computer code which was developed by the BDM Corporation for Rome Air Development Center in the 1970s.[63,64]

The hybridization process is totally transparent to the analyst once the types of interactions have been defined and the quantities

to be output by GEMACS have been specified. The use, coupling, and interaction of the various modules, as well as the transfer of data among the modules in the proper dimensions, are automatically handled by the overhead structure.[9]

The output of GEMACS is in the form of tabular data giving the current distribution on wires and surfaces, coupling between pairs of antennas, near- and far-field electric field strengths, and antenna terminal parameters.

The MOM method used in the code includes the thin-wire Pocklinton integral equation, pulse plus sine plus cosine expansion functions, point matching, and a charge redistribution scheme at multiple wire junctions. This scheme was used in the AMP (Antenna Modeling Program) Code.[74] It uses the Banded Matrix Iteration technique for solving the equations, which, as described earlier allows for a faster solution but sometimes may have problems with convergence. GEMACS uses the MFIE solution technique for patches, which can accurately only handle enclosed surfaces.

The GEMACS code is written in ANSI Standard Fortran and can run on a PC with OS/2, a VAX or SUN workstation, a MacII with Fortran (such as Microsoft Programmer's Workshop (MPW) and Language Systems Fortran), or any other machine with Fortran and enough RAM memory. The source code is provided, however, compiling and linking the programs is a fairly complicated process since the code is split up into several modules.

Permission for using the code must be obtained from Ken Siarkiewicz at Griffiths Air Force Base, Rome Lab, N.Y., (315) 330-2465. Various contractors supply the GEMACS code for distribution costs. Buddy Coffey at Advanced Electromagnetics in Albuquerque, NM, 505-897-4741, sells this code and gives support on in. His group helped write the code and now gives training on it. The cost for the standard version and users manual is $250. They also have enhanced versions of the code for Microsoft Windows and OS/2 for $1500 each. They also sell other source books, graphics codes, and distribute a newsletter.

2. BSC/NEC Code

As discussed in the section on the BSC code, the BSC UTD code has the option to use NEC MOM code input.

3. MOM/UTD Code

Sandia National Labs uses a hybrid MOM/UTD code to model complex electromagnetic problems.[65] They use a Hypercube parallel processing computer implementation (IPSC/860 system). For 25,000 unknowns, they have solved MOM problems in 9 hours at a rate of 2 Gflops. The MOM code is interfaced to the SRIM code (PO code) from the Univ. of Michigan to do the HF modeling.

4. Thiele Code

In this hybrid method, the UTD code is used to solve for a modified impedance matrix for the MOM solution. In effect, the UTD solution becomes the Green's function for the problem.[40] Piecewise sinusoidal basis functions are used in a Galerkin formulation which yields rapidly converging solutions to wire antenna configurations.

Work developing this code in the 1970s (by Dr. Thiele when he was at Ohio State University) was done for the Naval Research Laboratory for the specific problem of modeling antennas on spacecraft. The method used in this code is incorporated into the GEMACS code.

The University of Dayton does not normally distribute their code. They are doing development on the code, though, and use it to work on antenna modeling problems that they are contracted to examine. The contacts for this code are:

Gary Thiele (513) 229-2242
Dr. P.K. Pasala (513) 229-2683
Dr. R. P. Penno (513) 229-3984
University of Dayton
KL 262
Dayton, OH 45469.

F. Miscellaneous Antenna Design Codes

1. Ohio State Reflector Antenna Code

This is a code developed at the Ohio State University to compute the near and far-field patterns of reflector antennas with parabolic surfaces.[66] It can be used to predict the patterns of existing reflector antennas, design new reflector antennas, do radiation hazard calculations, and do EMC or coupling calculations with a reflector and small antennas.

This code uses a combination of the GTD method and the Aperture Integration (AI) method to compute the fields. Typically, AI, also known as the Aperture Field Method, is used to compute the main beam and near sidelobes, and GTD is used to compute the wide-angle sidelobes and backlobes.[66] Because these approaches are used, the minimum-size reflector that can be modeled is from 3 to 5 wavelengths in diameter.

A general piecewise linear reflector rim shape may be used. The required input data for the feed pattern is minimized by piecewise linear pattern fitting. The feed may be linearly polarized with any orientation or circularly polarized. A feed pattern option is available for a dominant mode horn feed in which the horn dimensions are input. Feed blockage is simulated by a physical optics model of a rectangular or a circular disk. Scattering from feed struts with circular cross section and piecewise linear axes can also be modeled. The code also has the capability to supply input to the NEC BSC code to model more complicated scatterers such as cylinders.[66]

Some of the limitations of the code are that the reflector surface must be parabolic. Also, the feed must be located near the focus, and the grid size used for aperture integration must be chosen sufficiently small to give a good representation of the aperture field distribution. The strut diameters should not be more than 10 wavelengths. The source of strut scattering is the geometrical optics fields from the reflector surface, other strut scattering mechanisms, such as direct feed scattering from the strut, are not modeled. This code provides significant improvement in the accuracy of near field calculations compared to the approximate EMC models previously used for reflector antennas. However, the code cannot be used to achieve accuracies greater than a dB, especially at low levels below the maximum fields.[66]

The code is obtained from Ohio State University as described above for $250. It comes with a code description manual and a user's guide with 11 examples.

2. Microstar Reflector Code

The Microstar Reflector Code is a current-integral program. It produces near-field and far-field antenna patterns for reflector antennas either parabolic, hyperbolic, or special shaped. The near-field pattern can have a planar or spherical output. The feed pattern input can be either an internally generated Sciambi[42] illumination, an existing file, an output of a previous Reflector run, or the feed pattern can be input point by point from measured data.[68] The feed can also be displaced axially or laterally. Cassegrain feed systems can be analyzed by computing the pattern from a hyperbolic subreflector and then using this as the feed for the parabolic reflector. The minimal allowable diameter for the main reflector is 3 wavelengths.

The code is written in Fortran and runs on a VAX computer. It can be obtained from the Microstar company which is located in Melbourne Florida.

3. Reflector and Lens Antennas: Analysis and Design Using Personal Computers

This is a group of programs for the analysis and design of reflector and lens antennas. All of the programs are short and provide the source code in ASCII so that they can easily be studied and customized. The programs are written in Fortran.

The programs and user's guide is available for $200 from:

Artech House, Inc.
685 Canton Street
Norwood, MA 02062

4. CAD for Linear and Planar Antenna Arrays of Various Radiating Elements

This program allows the user to design and analyze linear and two-dimensional planar arrays. A variety of element types,

excitations, ground interference and random error effects are allowed. The program includes various pattern functions of real and hypothetical radiating elements, as well as an impressive capability for generating amplitude and phase distributions.

The programs and user's guide is available for $300 from:

Artech House, Inc.
685 Canton Street
Norwood, MA 02062

5. Antenna Design Using Personal Computers

This is a group of simple antenna design programs for a PC. Many of the programs perform routine calculations, such as antenna directivity, array patterns, or transmission line design. Some of the programs treat slightly more sophisticated problems, such as horn design and wire antenna analysis using the method of moments. This set of programs is designed to be easy to use for anyone doing basic antenna analysis.

These programs are useful to get quick estimates for many kinds of antennas: wire antennas, arrays, horns, reflectors, and microstrip antennas. The source code is available and easily incorporated into other programs

The programs and user's guide (published in 1985) is available for $300 from:

Artech House, Inc.
685 Canton Street
Norwood, MA 02062

6. Antenna Software Limited

Antenna Software Limited is a British based company that markets antenna design software. The following is a list of some of the software that they currently offer and its cost:

APER	Circular Aperture Program	$180
COAX	Coaxial Structures	$4320
CORHORN	Professor Olver's Corrugated Horn Program	$9900
CORREC	Rectangular Corrugated Horn Program	$3960
CORRUG	Circular Corrugated Horn Program	$3960
REFSYN	Shaped Reflector Program	$3240

SPHREX	Spherical Wave Expansion Program	$4860
WIREZEUS	Method of Moments Program	$4500

These programs run on a PC or VAX machine. Executable code is normally supplied although they do offer the source code as well. These programs can be obtained from:

Antenna Software Limited
16 Peachfield Road
Great Malvern
Worcestershire, WR14 4AP, UK
010 44 684 574057 FAX 010 44 684 573509

7. Optical Ray Tracing Codes

There are several ray tracing codes available that can be applied to antenna modeling at high frequencies. Some of the more popular codes include Code V from Optical Research Associates in Pasadena, California, GENII from Genesee Optics Software, Rochester, New York, and OSLO from Sinclair Optics in Fairport, New York.

ASAP is another optical ray tracing code that can also handle diffraction. It can scatter off edges, and can be used for some simple systems such as modeling a dielectric lens for antennas. ASAP is available from Breault Research Organization, Inc., 4601 East First Street, Tucson, Arizona 85711, (602) 795-7885.

G. Graphics Codes

1. MacVerify

MacVerify is a geometry pre-processor for NEC and GEMACS which converts a data file into a 3-dimensional rotatable and scalable picture. This allows the user to determine if the structure he has built is accurate. It has the option of showing the structure as lines or solids. The code runs on a MacIntosh computer and is available from:

Concurrent Engineering Tools
P.O. Box 32080
Mesa, AZ 85275-2080
(602) 464-8208 Bob Tipton

The cost is $1250.00 or $3750 with a 5-year maintenance contract . A one year maintenance contract costs $500.

2. Super 3D

This is a graphics package for the MacIntosh computer used to draw 3-dimensional (3D) objects. The objects can be rotated and scaled either by themselves or as part of a big picture with many objects. The code produces nice graphics in contour or shaded 3D. Animation can also be done.

The data from the various antenna codes needs to be converted to input for this code. The data must be in a specific format so it would be useful to write a general interface program to input data easily.

The code is available from Silicon Beach Software for $300.

3. Swivel 3D

This is a 3D graphics package for the MacIntosh similar to Super 3D. It is available from PARACOMP for $459.

4. Kaleidagraph

For plotting field patterns from several of the codes, the MacIntosh Kaleidagraph plotting software (Synergy Software, Reading, Pa., 19606, (215) 779-0522) was found to be convenient. Any numerical file output can be easily imported into it just by knowing the format. Parts of the output can be plotted separately in linear or polar plots.

4. PV-Wave

PV-Wave is a software system for analysis and visualization of data. It runs on a workstation class computer. It is marketed by Precision Visuals, Inc., 6230 Lookout Road, Boulder, CO, 80301.

4. ConvexAVS

Convex AVS is software for analysis and visualization of data that runs on a CONVEX Super Computer. It is marketed by CONVEX Computer Corporation, 3000 Waterview Parkway, P.O. Box 833851, Richardson, TX 75083-3851, (215) 497-4000.

IV. Sample Problems

In this section some antenna design problems will be modeled with a few of the EM codes discussed in this report.

A. Flat plate with center monopole

The NEC MOM code, the Ohio State BSC UTD code, and the Ohio State ESP MOM code were compared modeling a flat plate with a center $\lambda/4$ monopole. In the first case, the plate was 2λ x 2λ in dimension. MacVerify was used to generate a plot (Figure 8) of the NEC wire configuration. Eight hundred wires of dimension $\lambda/10$ were used to model the plate and six to model the monopole. The BSC UTD and ESP MOM codes were also run for the same problem. For the BSC code, a single flat plat was used. For the ESP code, a flat plat automatically segmented into 180 patches ($\sim\lambda/7$ segmentation) was used.

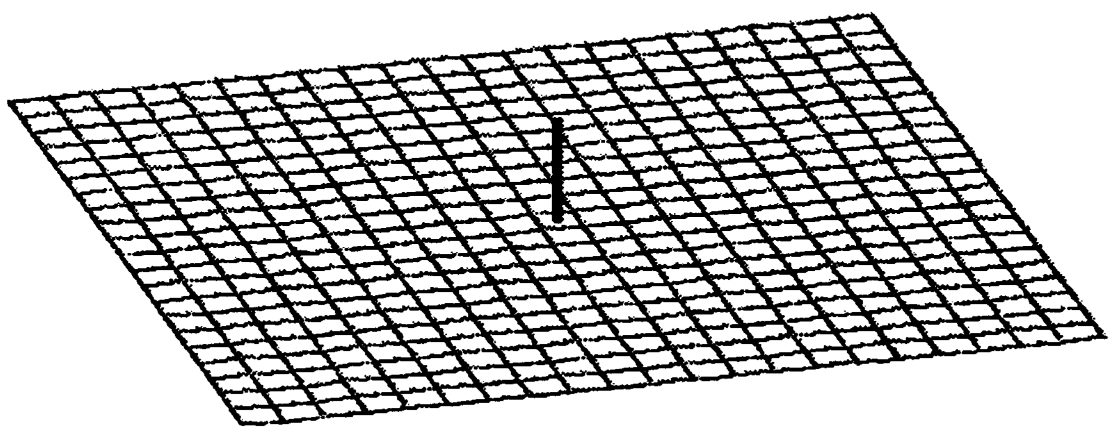


Figure 8. NEC wire modeling of flat plate with monopole antenna.

As can be seen in Figure 9, the results for the BSC and ESP code match fairly well. The NEC code output shows some erroneous rippling. This is due to the $\lambda/10$ segmentation of the wire grid, which should be increased to get a more accurate result. Normally, $\lambda/10$ segmentation is adequate for a MOM code, but this should be increased for critical areas around an antenna. The ESP MOM code gave more accurate results using patches and $\lambda/7$ segmentation. In general, using patches is a much more efficient and accurate method for modeling surfaces. The NEC code can only use patches if the area

is enclosed because, as described earlier, it uses a MFIE technique. For this problem, the ESP code is much easier to use than the NEC code because it automatically segments the plate. For the NEC code, the coordinates of all the wire segments must be specified. The BSC UTD code was also very easy to use for this problem.

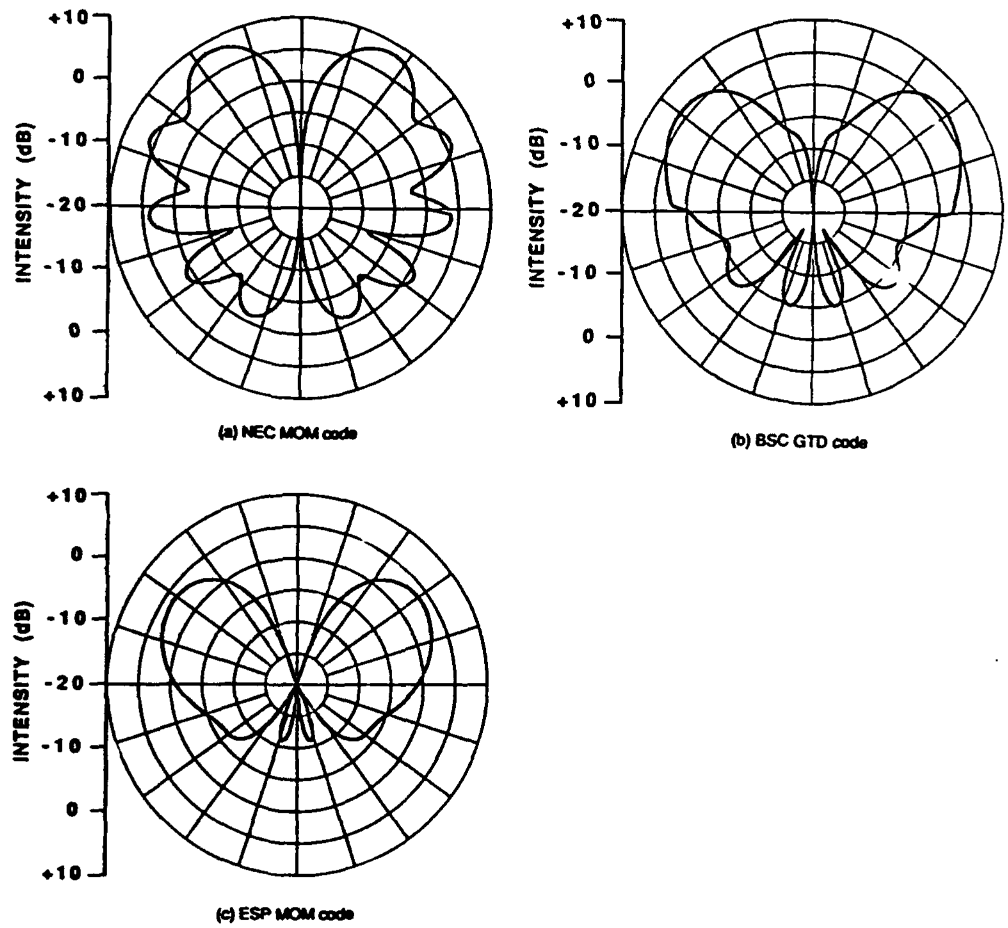


Figure 9. Far-field radiation pattern of 2λ x 2λ flat plate with center $\lambda/4$ monopole; (a) using NEC MOM code (b) using BSC UTD code (c) using ESP MOM code.

The plate was then increased to 4λ x 4λ and the runs redone. Figure 10 shows the results of this analysis for the BSC and ESP codes. The NEC code was not used because with $\lambda/10$ segmentation, this would require 3200 unknowns. Our NEC code is currently installed on a Mac IIfx computer with virtual memory, so a problem this size could be done, but would require several days of processing.

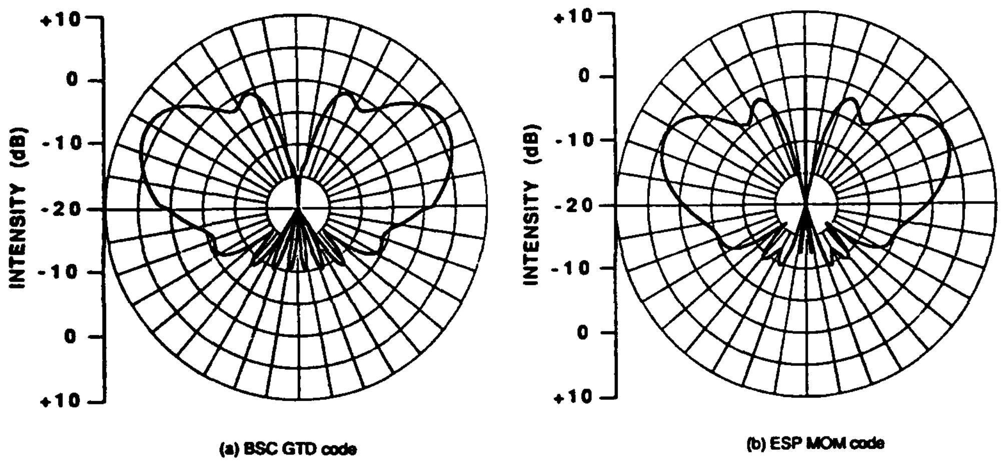


Figure 10. Far-field pattern of 4λ x 4λ flat plate with center monopole; (a) using BSC UTD code (b) using ESP MOM code.

As can be seen, the 4λ x 4λ runs were in closer agreement than the 2λ x 2λ runs. This is because the BSC UTD code has problems when the dimensions of the plates are near or below one wavelength. Also, the UTD code in general is not as accurate in this case because the monopole is so close to the flat plate. At this point, the approximations of ray tracing and diffraction break down.

This problem also highlights other deficiencies of the BSC code. The code cannot determine input impedance and the intensity profile is not normalized because the code does not integrate the power over the whole area.

The edge of a ground plane (or any sharp edge) causes reflections in antenna systems and so will radiate. This radiation will interfere with the radiation from the antenna and cause ripples in the field patterns. An elementary method (based on interference principles) of calculating where ripples in an antenna pattern come from is to divide 57^{o} by the peak to peak separation of the ripples in degrees. This gives the number of wavelengths away that the interference comes from. This method can be verified by this example. Figure 10 shows ripples spaced approximately 30^{o} apart, which would accurately indicate an edge $\sim 2\lambda$ away from the antenna. Another BSC UTD run was done of a monopole centered on an 8λ x 8λ plate. As shown in Figure 11, for this run the ripples are spaced approximately 15^{o} apart, indicating an edge 3.7λ away from the antenna.

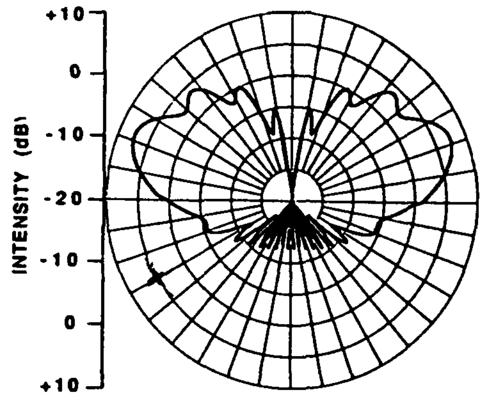
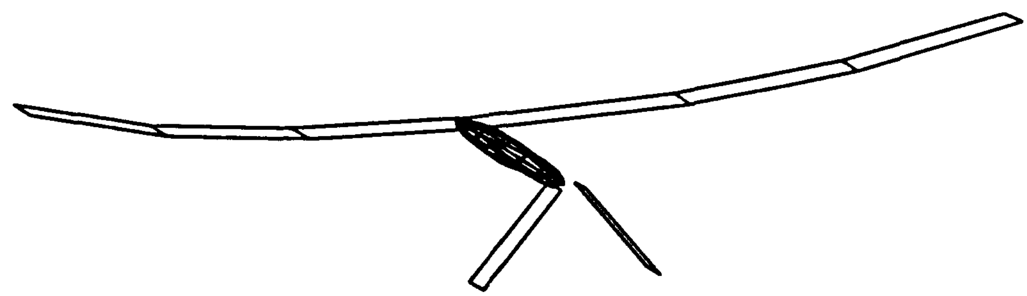


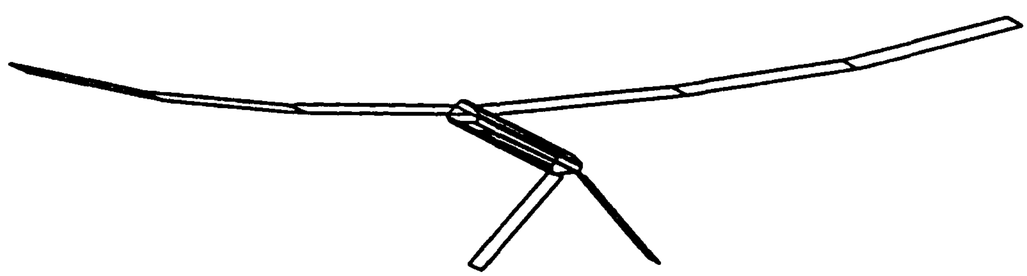
Figure 11. Far-field pattern of 8λ x 8λ flat plate with center monopole using BSC UTD code.

B. High Altitude Plane

A plane with a 2.25 GHz $\lambda/4$ monopole mounted on its belly was modeled with the Ohio State BSC and NEWAIR UTD codes. The Super3D graphics program was used to visualize the configurations (Figure 12).



(a) NEWAIR model



(b) BSC model

Figure 12. High altitude plane with monopole antenna.

This problem illustrates the limitations of the BSC and NEWAIR codes. The NEWAIR code needs to mount the antenna on a composite ellipsoid. This code cannot model dielectric surfaces and skins. The rest of the aircraft needs to be modeled with flat plates. The BSC code can model curved surfaces such as cylinders and composite ellipsoids, however, the antenna cannot be mounted on a curved surface. For this code, the body of the plane was modeled as a set of flat plates. In actuality, the body of the plane to be modeled would be most accurately modeled by a set of curved and flat plates. The

propeller is made up of dielectric material and so could be ignored in the models.

Figure 13 shows the predicted far field radiation patterns in the theta direction around the pitch and roll axes (around the pitch axis the angle cut is through the main body of the aircraft, around the roll axis the angle cut is through the wings of the aircraft).

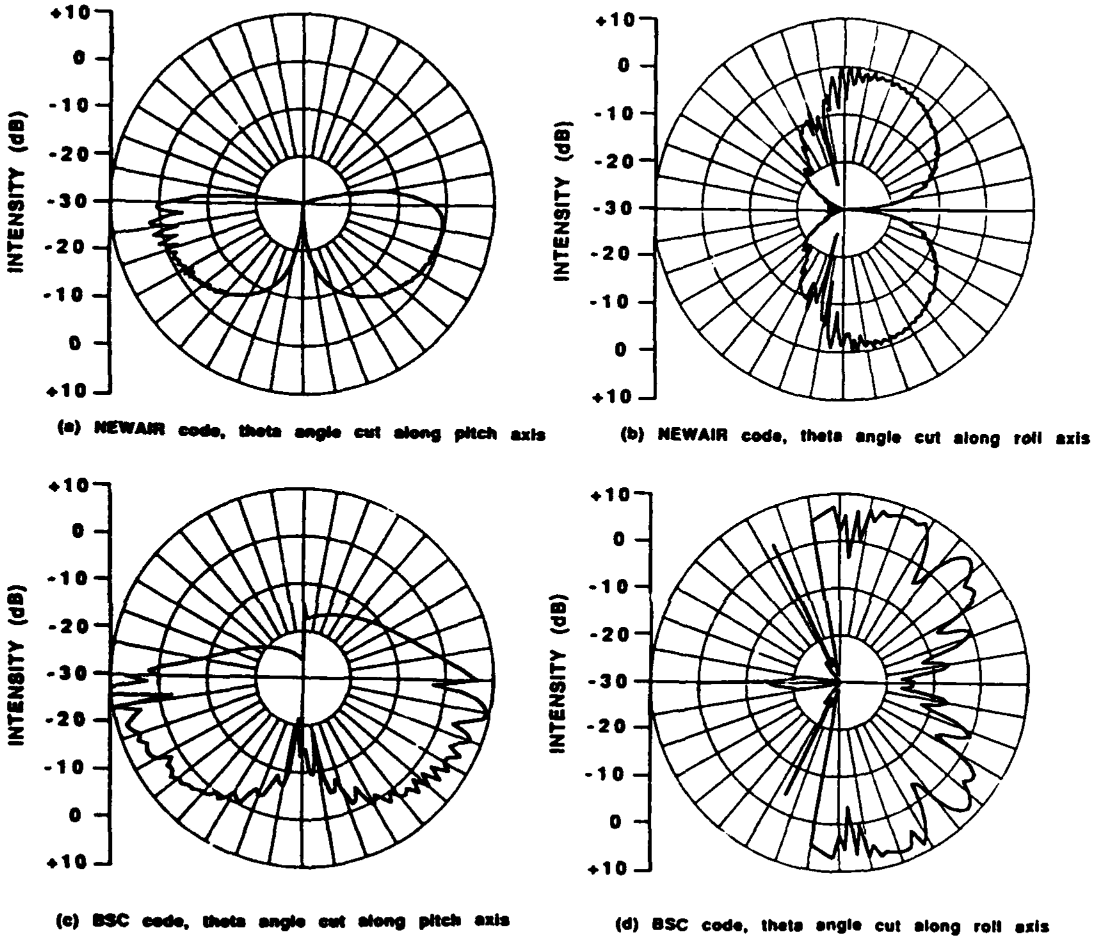
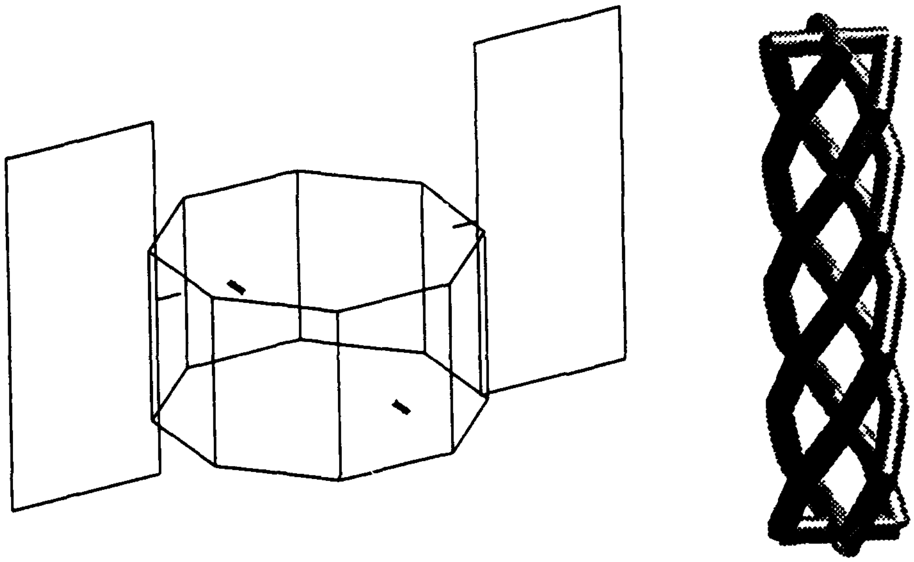


Figure 13. Far-field radiation patterns of high-altitude plane, (a&b) using NEWAIR code, (c&d) using BSC code.

The BSC code patterns are more erratic and angular because of the sharp edges on the flat plates. The differences between the two codes' output is accentuated because, although the outputs are plotted on the same scale, the outputs are not normalized. The BSC code output is a few dB higher than the NEWAIR code output, but this is just because the two codes do not use the same method of determining the relative magnitudes of the fields.

C. Quadrifilar Helical Antenna on a Spacecraft

The NEC code in combination with the BSC UTD code was used to model a quadrifilar helical antenna on a spacecraft. Figure 14a shows the spacecraft with the antenna and solar panels attached and Figure 14b shows the helical antenna itself. The quadrifilar helix has four wire segments which wind down around a cylindrical core. The operating frequency is 2.2 GHz.



(a) (b)

Figure 14. (a) Helical antenna on spacecraft, (b) helical antenna.

The modeling method used for this system was first to model the helical antenna pattern alone and with only a ground plane present. The NEC code is used for this. It is an ideal code to use for this type of antenna since the antenna consists entirely of wires. Figure 15 shows the electric field intensity with vertical polarization without a ground plane present. This compares nicely to quadrifilar helical antenna experimental patterns.[69]

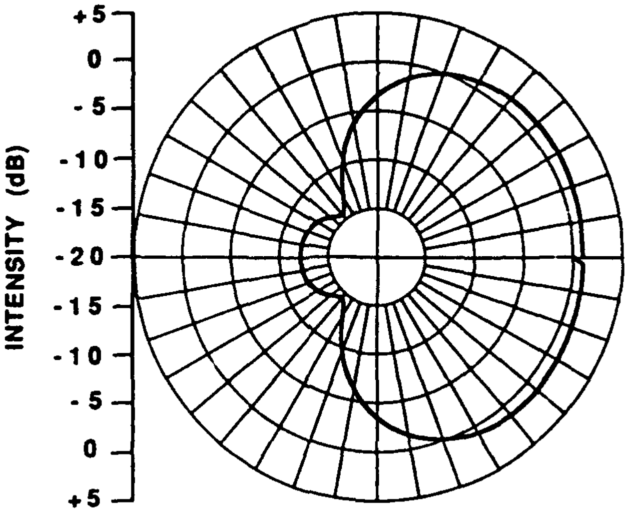


Figure 15. NEC code predicted radiation patterns for helical antenna without a ground plane.

The NEC code outputs the currents and geometries of all the wires in the model. This can then be directly input to the BSC code along with the spacecraft structure. The BSC code was written to accept the NEC output format so this is a very simple process. The BSC code then uses the UTD method to compute the new electric field patterns. Figure 16 shows the results for the total field intensity (the helical antenna produces circularly polarized radiation). The pattern cut is around the central axis of the spacecraft.

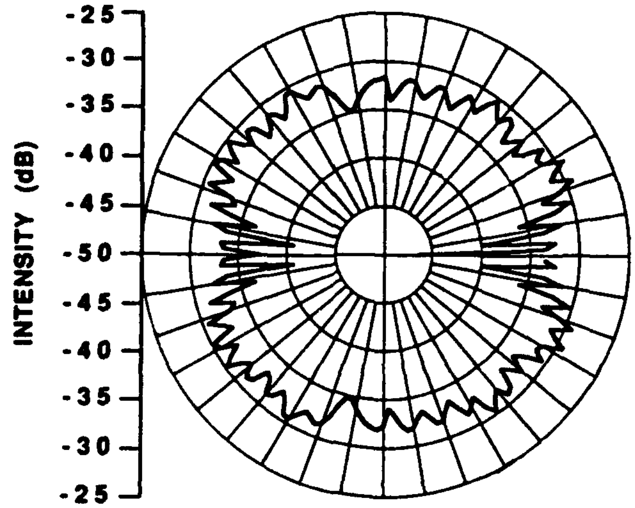


Figure 16. BSC code predicted radiation patterns for helical antenna on spacecraft using NEC code input.

The total pattern is similar to the pattern of the helix alone but has 2-4 dB ripples caused mainly from the interference pattern created by the edge of the plate the antenna is mounted on. The edges are 9.32 to 13.5 inches (~6.4 wavelengths) away from the antenna so the ripples, as discussed in Sample Problem A, should be $56^o/6.4$ or 8.75^o apart.

This hybrid MOM/UTD technique enables the antenna modeler to accurately model a high frequency antenna and its environment. This is a valuable technique which can cover a wide range of antenna problems. The primary limitation is that it can only model wire antennas. Other limitations are limitations of the NEC code. Other wire antenna codes could also be used, however, their output would need to be converted to the specific output that the BSC code requires.

This hybrid technique cannot model dielectrics or surface patches, but probably could easily be extended to surface patches.

D. Dielectric Lens

The ASAP ray tracing code was used to model a dielectric lens made up of 25 layers with varying dielectric constants. In this case the phase center of the antenna is assumed to be located at the center back of the lens and all the rays are directed from that point. Figure 17 shows the trace of the rays through the lens. The lens has the effect of changing the phase center of the antenna to a point inside the lens. The outgoing angles of the rays can be shifted depending on the dielectric constants of the layers of the lens.

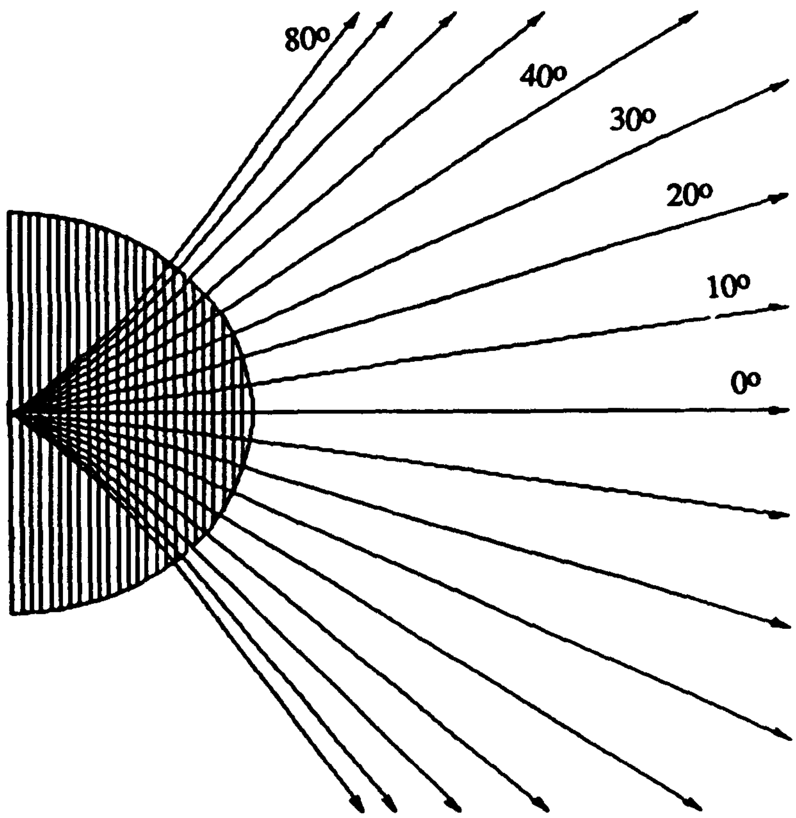


Figure 17. Dielectric lens modeling using ray tracing.

V. SUMMARY

All of the antenna analysis codes have their limitations and the antenna design engineer must be well educated on their use and capabilities. The best code for the particular design can then be chosen and preferably the design run on several of the codes to compare their outputs to make sure no anomalies occur.

Good agreement can be made between analysis and testing, however, the general consensus from this study was that analysis cannot be used as a complete replacement for testing. It can best be used as a first cut design tool, as a teaching tool, and as a design tool once measurements have been made to establish the validity of the model.

The importance of general CAD codes for automatically managing the geometrical modeling becomes more and more pronounced as the complexity and capabilities of the antenna codes increases.

Along with advances in analysis tools, similar advances have been made in measurement tools, so that actual measurements can be made with much more ease and speed than before. The Scientific Atlanta system can take 5000 measurements/second. Other companies such as Hewlett-Packard have similar systems.

For the specific application of modeling antennas on spacecraft the results of this report show that high frequency techniques such as GTD are necessary for frequencies much above 300 MHz. Three techniques are available for this type of analysis:

1. The GTD method alone can be used with the antenna modeled as a simple dipole (or dipoles), slot , or combination of these. This technique is fine except for antennas that cannot be modeled so simply.

2. The antenna can be modeled with a MOM, FE or FDTD code hybridized with a GTD code.

3. The known (either by calculation or experiment) far-field pattern of the antenna alone is converted to a near field pattern by the use of Fourier transforms. This pattern is then used as input to a GTD code which tracks the reflected and diffracted rays through the antenna environment to be modeled.

Modeling more than one antenna will normally require several computer runs to be made. For each run, one antenna will be analyzed with the other antennas input merely as scattering objects. Coupling calculations can be made but this requires using a MOM, FE or FDTD code. These codes can be run to analyze sections of the spacecraft.

Using super computers or parallel processing machines, modeling antennas on spacecraft can be done using more accurate techniques such as the MOM or FE methods. Overnight runs involving 50,000 unknowns can be done with these resources. For an FDTD code, runs with 700,000 cells can be done overnight. This type of work is state-of-the-art and is not yet readily available to the engineering community. For codes capable of running very large problems, considerable effort goes into developing and using CAD preprocessing programs.

Table XI lists past, current, and predicted future computer capabilities for EM code performance using the MOM, FE or FDTD methods.

Table XI. Past, Current, and Future Computer Capabilities for EM Modeling[52]

	5 Years Ago	Today	5 Years from now
Memory	1 MWord	500 MWords	100 GWords
Speed	10 Mflops	1 Gflop	100 Gflops
Maximum configuration size at 1 GHz (λ=1')	1' x 1' x 1'	30' x 15' x 2'	200' x 100' x 15'

The numbers in Table XI represent state-of-the-art capabilities. To give a reference to compare these numbers to, the XMP CRAY computer runs at a maximum speed of ~120 Mflops per processor and has two processors. There is also a smaller CRAY, the YMP-EL, which runs at ~30 Mflops. The VAX 11/780 runs at approximately 0.5 Mflops. These numbers are all dependent on the type of problem the computer is running. Normally, several benchmark problems are run on the computer to gauge its performance. Parallel computers currently scale from 8 processor

hypercubes to a 500 processor mesh architecture, which is currently the world's most powerful machine.

The codes that the authors found to be most useful and to have the most potential were the NEC code, the ESP code, the EMAS code, the TSAR code, the BSC code, the GEMACS code, the Reflector Code, and the GMULT code.

It is also crucial to be able to verify the code input with graphics software. Three dimensional structures are difficult to visualize and the only way to make sure of the proper input is to plot it out in several rotational angles. Most of the codes have graphics software which only works on a specific machine. It is also possible to use some general purpose graphics software and then write a program to convert the input from one format to another.

There is a large amount of research going on developing new codes and modifying current codes to allow them to model more sophisticated antenna systems. Much of the work is being done by private companies, government labs, and universities. Unfortunately, this work is not easily accessible either because the codes are proprietary or else not designed to be used by anyone other than the developer. Good sources of information regarding research in the antenna modeling field are journals and also conferences. The annual IEEE Antennas and Propagation Society International Symposium usually held in the summer has many sessions devoted to antenna modeling. The Applied Computational Electromagnetics Society (ACES) has a yearly conference held in the spring.

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